DESIGN AND CONSTRUCTION OF AN EXPERIMENTAL APPARATUS FOR HEAT TRANSFER STUDIES IN DISSOCIATING IODINE VAPOR

by

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and

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Chairman, Departmental Committee on
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ABSTRACT

DESIGN AND CONSTRUCTION OF AN EXPERIMENTAL APPARATUS FOR HEAT TRANSFER STUDIES IN DISSOCIATING IODINE VAPOR

John Donald Christie

Dietrich Wilhelm Brunner

Submitted to the Department of Mechanical Engineering on May 20, 1960 in partial fulfillment of the requirements for the degrees of Master of Science.

A closed loop tunnel and test section have been designed to enable the experimental determination of the heat transfer rate to a gas in laminar flow for varying degrees of dissociation. The iodine gas, circulated around the tunnel, enters the tubular two inch test section at a pressure between .001 and 1 atmosphere, a temperature between 250° and 400°F, and is subjected to a constant test section wall temperature which may be varied up to 1500°F. The apparatus is constructed principally of six inch porcelain coated steel pipe and fittings.

The thesis consists of the following major parts: (I) Determination of closed loop tunnel in preference to a blow-down system; (II) Test section heat transfer analysis, design, and instrumentation; (III) Design of the closed Loop tunnel; (IV) Proposed test operation and presentation.

Thesis Supervisor: George Brown

Title: Assistant Professor of Mechanical Engineering

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We wish to express our sincere appreciation to Professor George Brown and Professor S. William Gouse for their constructive guidance throughout the course of this thesis.

We would also like to thank Professor Joseph Kaye for his enthusiastic assistance and for affording us the opportunity to work on this project.

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INTRODUCTION

Dissociation and ablation phenomena, in view of their importance in fast developing space technology, are being examined by many groups to learn more about their nature. This thesis is concerned with designing an experimental apparatus to obtain reliable heat transfer measurements in a dissociating boundary layer. The iodine wind tunnel and test section designed as a part of this thesis are believed to be a unique approach for obtaining such data.

Preliminary work on this project conducted last year led to the choice of iodine as the substance best suited for dissociation and ablation experiments. The scope of this thesis is limited to dissociation experiments but the experimental program can be broadened in the future to include ablation studies. The dissociation reaction for iodine vapor is simple ($I_2 \rightarrow 2I$), limiting the gas stream to a mixture of only two components. The degree of dissociation in the vapor phase can be varied between 0 and 90% within reasonable ranges of temperature (400°F to 1500°F) and pressure (1 to 0.001 atmospheres). Both the physical and thermodynamic properties of iodine vapor are known. The disadvantages of using iodine are that it is semi-toxic and extremely corrosive.

Based on the relative advantages and disadvantages of a blow-down and closed loop system, the latter was chosen for concentrated analysis. A closed loop tunnel to be constructed principally of corrosion resistant porcelain coated

steel pipe and fittings was designed. The tunnel, about ten feet high and three feet wide, consists mainly of six inch diameter pipe with a two inch diameter test section. Several test pieces were made to test various seals and connections for use in the low pressure tunnel and to determine how various materials stand up in an iodine atmosphere.

In the test section, the method of measuring the heat transfer to the gas will be through the electrical input to heater elements wound around the tube which contains the iodine flow. By controlling the value of the inside tube wall temperature and by varying the pressure level in the tunnel, various degrees of dissociation may be obtained at the gas-tube wall interface.

This thesis consists of the following major parts which deal with the above mentioned apparatus in detail: (I) determination of a closed loop tunnel design in preference to a blow-down system; (II) test section design, analysis and instrumentation; (III) design of the closed loop wind tunnel; (IV) proposed test procedure and presentation of results.

I. PRELIMINARY DESIGN

A. SCOPE OF EXPERIMENTS

Once the working substance, iodine vapor, for ablation and dissociation experiments had been chosen, it was necessary to define the scope of experiments to be made. The properties of iodine vapor are presented in Appendix A. A review of all possible experiments that might be conducted in an ablation and dissociation study was presented by Eastman (1)[1] and is reviewed in Table I on the following page. It became apparent that one piece of apparatus that could be used to make all these experiments would be impractical at this time. It was decided, therefore, to limit the initial program to an experimental investigation of the effect of varying degrees of dissociation on heat transfer rates between iodine gas in laminar flow and a test section or model at a different temperature. The dissociation reaction for iodine vapor is $I_2 \rightarrow 2I$. Although the present design has been done on the basis of this objective, it may be possible to modify the apparatus to increase the scope of experiments. It is desirable to get some experimental results to increase our knowledge of the effect of chemical reactions on heat transfer before any modifications or additions are planned.

1 Numbers in parentheses refer to items in Bibliography.

TABLE I

Summary of Dissociation and Ablation Experiments

In the description of experiments, To is the temperature of the gas entering the test section, Tw is the temperature of the test section surface at which the heat-transfer measurements are made, and Po is the pressure of the gas flowing in the test section.

TEST SECTION WALL MATERIAL	RELATION OF To to Tw	TEST GAS	DESCRIPTION OF TEST
Inert	$T_o > T_w$	I_2	To and Po such as to supply I_2 gas. Check fluid flow and heat-transfer characteristics of an I_2 gas laminal boundary layer.
Inert	$T_o < T_w$	I_2	To and Po such as to supply I_2 gas to the test section. Tw, To, and Po can be varied so as to give varied degrees of laminar boundary layer dissociation, and study effects on heat-transfer rate.
Inert	$T_o > T_w$	I_2+I	To and Po such as to supply I_2+I gas. The test section surface is relatively cool so that the effects of iodine recombination on the heat-transfer rate can be studied.
I_2 solid	$T_o > T_w$	I_2	To and Po such as to supply I_2 gas. By varying flow properties or by cooling the test section surface the sublimation rate can be controlled and the effects on heat-transfer studied.

TABLE I (cont.)

TEST SECTION WALL MATERIAL	RELATION OF T_o to T_w	TEST GAS	DESCRIPTION OF TEST
I_2 solid	$T_o > T_w$	I_2+I	T_o and P_o such as to supply a mixture of I_2 plus I gas. The effects of dissociation and sublimation on heat transfer can be investigated.
I_2 solid	$T_o > T_w$	Inert	Control T_w such that test section surface sublimes and diffusing gas dissociates in laminar boundary layer, and effects on heat transfer studied.

B. BLOW-DOWN VERSUS CLOSED LOOP TUNNEL

1. Introduction

Two basic experimental configurations were considered for the test program. They were a blow down tunnel and a closed loop tunnel. The final decision to use a closed loop tunnel was based on the relative advantages and disadvantages of the two different tunnel types and of the test sections that might be used in each case.

Several things would be common to both tunnels. Because of material capabilities, it is advisable to restrict the maximum operating temperature to 1500°F (approximately 1090°K). Figure 13, Appendix A2 indicates that at temperatures up to this value, and at pressures between 1.0 to 0.001 atmospheres, the mole fraction of dissociated iodine ranges between 0 and .85.

The maximum velocity in the test section should be limited to approximately 100 feet per second, which at 450°F corresponds to a Mach number of 0.2, thus allowing the flow to be considered incompressible. This is desirable because high speed flow is more difficult to obtain, and experimental evaluation of compressible flow would be more complicated than incompressible flow. For a Mach number of 0.2 or less the static pressure is within 3% of the stagnation pressure. It is also desirable to keep the flow in the apparatus in the laminar region, since if theoretical expressions are later to be developed to compare with the experimental data,

this is possible, if at all, only for laminar flow. Consequently the diameter Reynolds number for a tube is restricted to approximately 2300 or less, and the length Reynolds Number for a model has a maximum value.

The velocity, diameter Reynolds number, and mass flow rate of iodine vapor (I_2) in a two inch diameter tube are tabulated at different pressure levels in Table II on the following page. The first tabulation is for an iodine temperature of 500°K (440°F) and the second is for a temperature of 1100°K (1520°F).

2. Blow-Down System

A schematic diagram of a possible blow-down system is shown on p. 9 in Figure 1. In the boiler iodine vapor is generated from solid iodine and then heated to 1000°F. The hot iodine vapor then enters a test section where heat is transfered from the iodine to the tube walls. After the iodine vapor leaves the test section, it must be condensed or resolidified.

The advantages of a blow-down system are that experimental runs would be of short duration and that iodine contamination would not be as critical as it is in a recirculating system. Contamination is to be avoided since meaningful interpretation of dissociation test results can only be made if all tests are conducted with pure iodine gas. Contaminants would alter the mean gas properties to an unknown value. This system would also be easier to use for

TABLE II

Flow Characteristics For 2" Diameter Tube

T = 500°K (440°F)

Re = Reynold's No.

$\bar{v}$ (ave.vel.) ft/sec

P (atm)	1	10	100
1.0	4,180	41,800	418,000
.1	418	4,180	41,800
.01	42	418	4,180
.001	4.2	42	418

W = Flow Rate (#/Hr)

$\bar{v}$ (ave.vel.) ft/sec

P (atm)	1	10	100
1.0	30.4	304	3040
.1	3.04	30.4	304
.01	.30	3.04	30.4
.001	.03	.30	3.04

T = 1100°K (1520°F)

Re= Reynold's No.

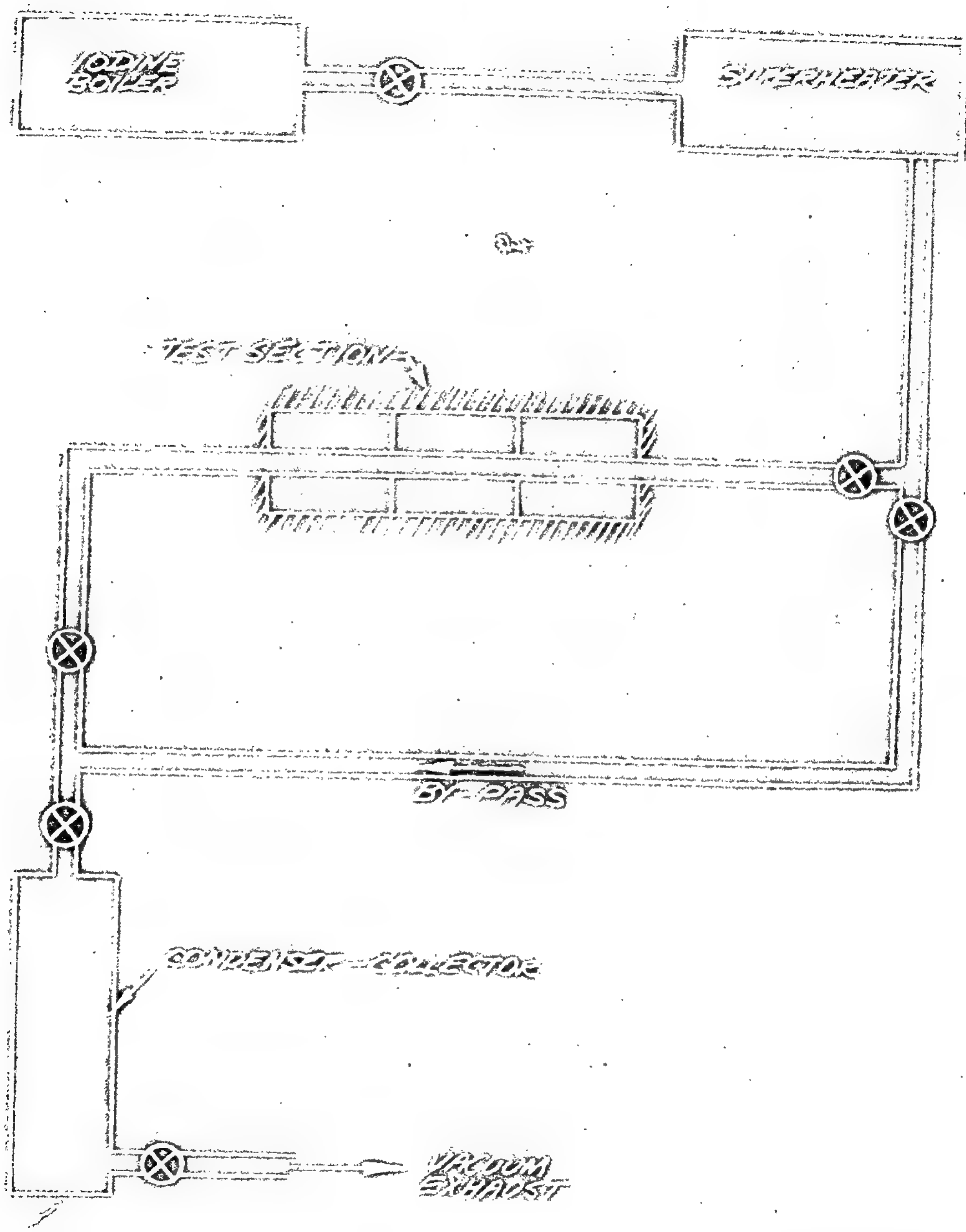
$\bar{v}$ (ave.vel.) ft/sec

P (atm)	1	10	100
1.0	907	9070	90700
.1	91	907	9070
.01	9	91	907
.001	.9	9	91

W = Flow Rate (#/Hr)

$\bar{v}$ (ave.vel.) ft/sec

P (atm)	1	10	100
1.0	13.8	138	1380
.1	1.38	13.8	138
.01	.14	1.38	13.8
.001	.01	.14	1.38



NOT TO SCALE

BLOW DOWN SYSTEM SCHEMATIC

FIGURE 1

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sublimation experiments than a closed loop.

The disadvantages of a blow-down system are that it would be difficult to obtain steady state results because of the limited duration of test. Keeping the iodine flow into the test section constant would be difficult with a small boiler. The condenser size required to condense or resolidify the iodine vapor after the test section would have to be prohibitively large because of the low heat transfer coefficients obtainable with iodine due to its low thermal conductivity ($h \approx 0.1 \frac{Btu}{hr\ ft^2 {}^\circ F}$ for typical flow rates - see page 23). This large condenser would have to be constructed of corrosion resistant materials for use with iodine. Large amounts of iodine would be required for the operation of this system. For a run of an hour's duration using iodine gas at 1500°F with the Reynolds Number of 2300 in a two inch diameter flow tube would require a batch of approximately 30 pounds of iodine. Since tests in a blow down tunnel are batch processes, the capacity of the boiler and the condenser collector must be increased if the desired running time is increased.

In considering the test section for a blow-down system, it appears that the tube walls alone would have to be considered as the model (i.e. internal flow) because cooling any model placed in the flow would be extremely difficult and the cross sectional area of the test section would have to be increased to insert a model in it. This

would necessitate larger flow rates and make the boiler and condenser collector difficulties worse.

The amount of heat transfer from iodine at 1000°F to the walls of a two inch diameter tube 3 feet long at 500° is given by $q = hA\Delta T$. If the flow is laminar the the heat transfer coefficient is approximately 0.1 $\frac{\text{Btu}}{\text{hr ft}^2\text{°F}}$ therefore $q \approx 80$ Btu/hr. This heat transfer in the test section would be determined experimentally by measuring the heat transfered from the tube walls to a cooling fluid. The heat transferred to the fluid is $q = w\ c_p\Delta t$. For the order of magnitude of q expected, the product of $w\Delta t$ for the fluid would be too small to get accurate heat transfer measurements. Experimental difficulties would be present because of conduction heat losses along the tube and other losses through insulation. These losses could not be eliminated completely for an unsteady state test. The relative magnitude of the total heat transfer from the iodine compared to the losses mentioned is not high enough to get reliable experimental results. To get more heat transfer from the iodine by increasing the inside heat transfer coefficient to approximately 10 would require a Reynolds number of 114,000. The velocity in the test section for this Reynolds number would have to be equal to $130/p\ \frac{\text{ft.}}{\text{sec}}$, where p is the iodine pressure in atmospheres. If the restriction of incompressible flow is to remain, the velocity could not exceed approximately 125 $\frac{\text{ft.}}{\text{sec.}}$. Therefore

experimental runs could not be made for iodine pressures less than one atmosphere. From the standpoint of dissociation this is impractical.

The disadvantages of a blow down system are such that they outweigh its advantages. A closed loop system is more practical and does not have as many disadvantages.

3. Closed Loop System

A schematic diagram of the final closed loop tunnel is shown in Figure 2 on the following page. It consists of six inch piping through which iodine vapor is circulated continuously, entering as a cool (250-450°F) gas into a test section whose surface is at higher temperatures. To operate a closed loop system the apparatus must first be evacuated with a vacuum pump. The apparatus is then heated to a sufficiently high temperature to keep iodine a vapor. Iodine vapor, generated in a boiler, is then allowed to enter the apparatus. A fan in the system recirculates the gas through the test section and around the rest of the loop.

The advantages of a closed loop are that the iodine capacity is low, that steady state operation is possible, and that a condenser is needed only for periodic emptying and not during experimental runs. Because of sealing problems, the circulating gas must be at a relatively low temperature while the test section walls or model are at a high temperature. The disadvantage associated with this

CLOSED LOOP SYSTEM SCHEMATIC

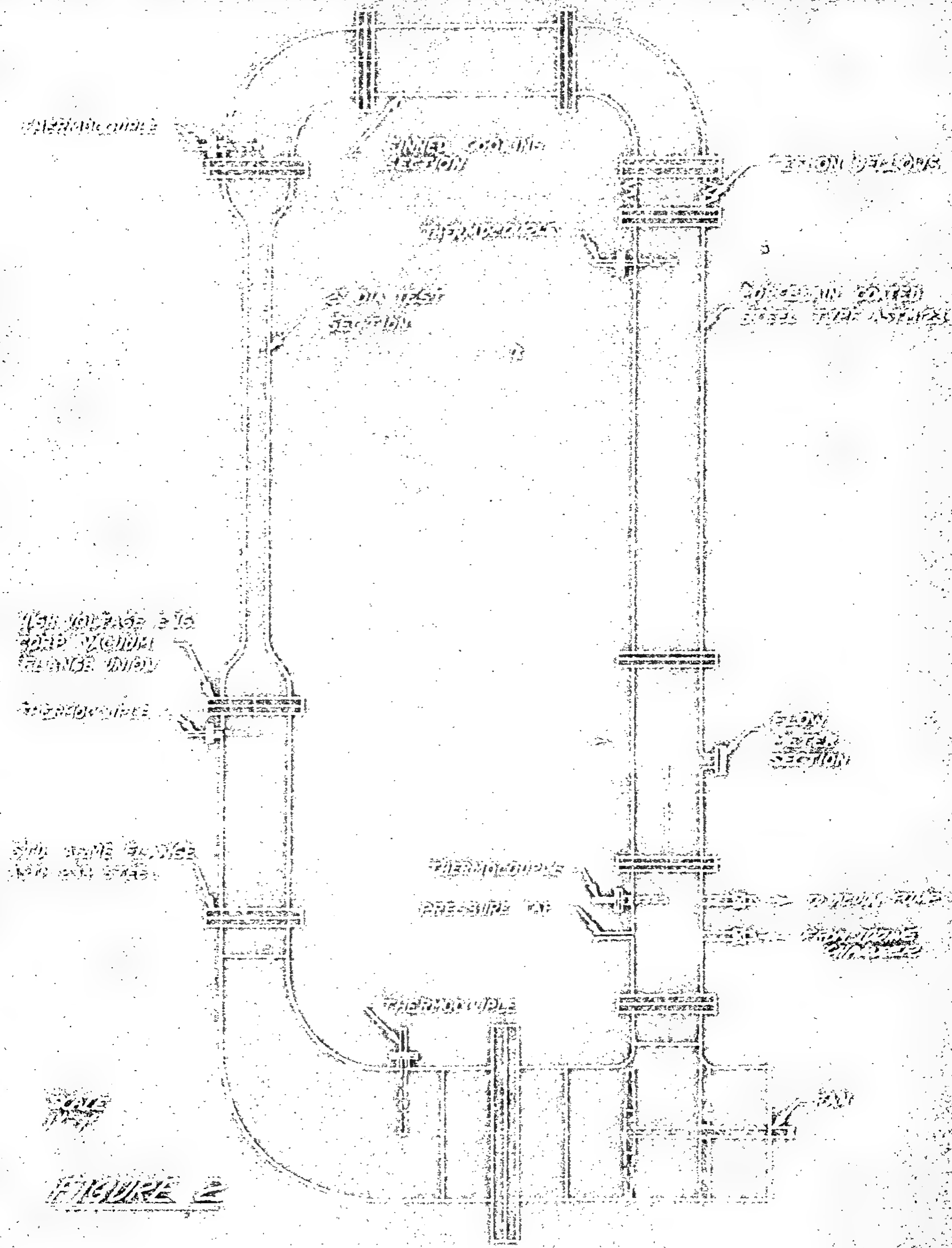

FIGURE 2

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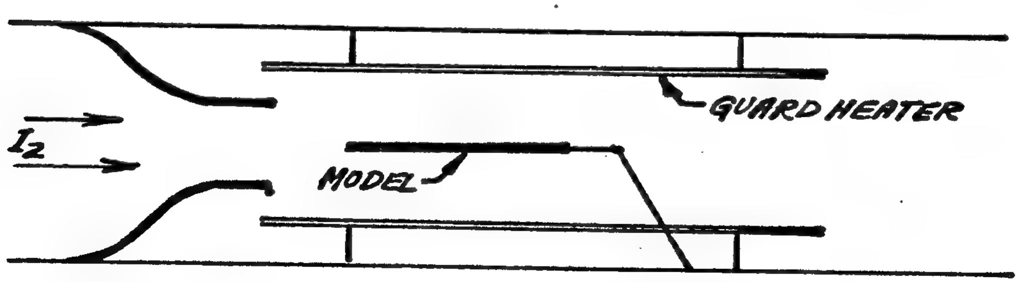
is that sublimation experiments would be difficult to perform because time is required to reach steady state, and the upper temperature limit of the circulating gas would limit sublimation rates. Difficulties could arise because any corrosion product or other contamination of the iodine vapor that exists would accumulate and be recirculated. Air leakage into the system must be completely eliminated or it will build up when the apparatus is running. It is expected sealing difficulties will present one of the major problem areas for a closed-loop system.

Two basically different types of test sections were proposed for use in the closed loop tunnel, one being a model in a free jet and the other being internal flow.

Two different model shapes for a free jet test section were considered. The first model considered was a flat plate. The design shown below in Figure 3 indicates how the plate would be placed in a jet from a 2" nozzle and protected by guard heaters to minimize radiation losses.



Model in a Free Jet

Figure 3

TABLE III

RE_D=2"	RE_X=3"	$\bar{h}(\frac{Btu}{Hr Ft^2 °F})$	$q_C(\frac{Btu}{Hr})$	$q_R(\frac{Btu}{Hr})$ with 5°ΔT Between Model and Wall Shield
2140	1294	.312	7.15	5.5
428	259	.140	3.21	5.5
43	26	.004	1.01	5.5

The results of heat transfer calculations for a 1 x 3 inch plate inserted in a free jet are shown above in Table III. The heat transfer rates tabulated are for one side of the plate. The heat transfer by radiation is calculated assuming a 5°F temperature difference between the model surface and the guard heater. Sample calculations are presented in Appendix B1. The results indicate that the magnitude of the radiation heat transfer is the same as that of the convective heat transfer. Consequently reliable results could only be obtained if model and guard heater temperatures could be controlled to within one degree. At temperatures af 1500°F such accuracy would be quite difficult.

Using a cone as a model was also considered. Approximately the same relations exist between convective and radiation heat transfer, except that there is additional radiation out the ends. Except for this fact a cone shaped model would be preferable over a flat plate because its

symmetry eliminates edge effects.

An internal flow test section utilizes the tube walls, through which the iodine flows, as the test model. In considering this type of test section,flow between parallel plates and flow in a tube were considered. Tube flow is preferable to flow between parallel plates. When two parallel plates are heated separately, their temperatures may differ and radiation heat transfer between the plates will occur. This radiation heat transfer would be undesirable. In the case of a tube there is axial symmetry and no net radiation heat transfer will occur between different parts of the tube if all are the same temperature.

Flow in a tube was the primary type of internal flow considered because of its symmetry and relative lack of radiation heat transfer difficulties. It was investigated because it was expected that by using appropriate insulation and shielding techniques, the heat transfer to the dissociating iodine vapor could be determined without expecting too large an error due to other modes of heat transfer (i.e. radiation and conduction losses). A detailed description of the final tubular test section design is presented in the following section.

4. Conclusion

The feasibility of the closed loop system and the relative lack of difficulties associated with it compared to the blow-down system prompted the choice to concentrate further effort on the closed loop tunnel. In this closed

loop system it appeared the main difficulty would be sealing effectively to prevent leakage and contamination, but it was felt this could be overcome.

II. TEST SECTION DESIGN

A. HEAT TRANSFER ANALYSIS

In the previous section it was stated that meaningful experimental results could be obtained for a test section based on internal tube blow. A schematic diagram of this type of test section is shown in Figure 4 on the following page. Heat transfer to the iodine vapor will be measured by measuring the electrical heating input to the heaters stationed along the test section length. Heat transfer losses other than the heat transferred to the iodine will be shown to be of relatively small magnitude. These additional heat transfer modes are: (a) radiation out the ends of the two inch diameter, three foot long tube containing the flow, hereafter referred to as the test tube; (b) axial heat conduction from the high temperature test tube to the lower temperature nozzle and diffuser; and (c) radial conduction between the test tube and the guard heater.

The appropriate control of these three possible losses will be accomplished by: (a) considering the middle foot of the three foot test tube as the test data section, thereby reducing radiation losses out the two ends of this center test data section to negligible amounts; (b) supplying additional power to the end heaters of the test tube so that the test tube wall temperature is maintained at the desired constant value along its length despite axial losses at the ends by conduction, thereby reducing axial conduction at the center test data section to zero; (c) installing a

TEST SECTION SCHEMATIC

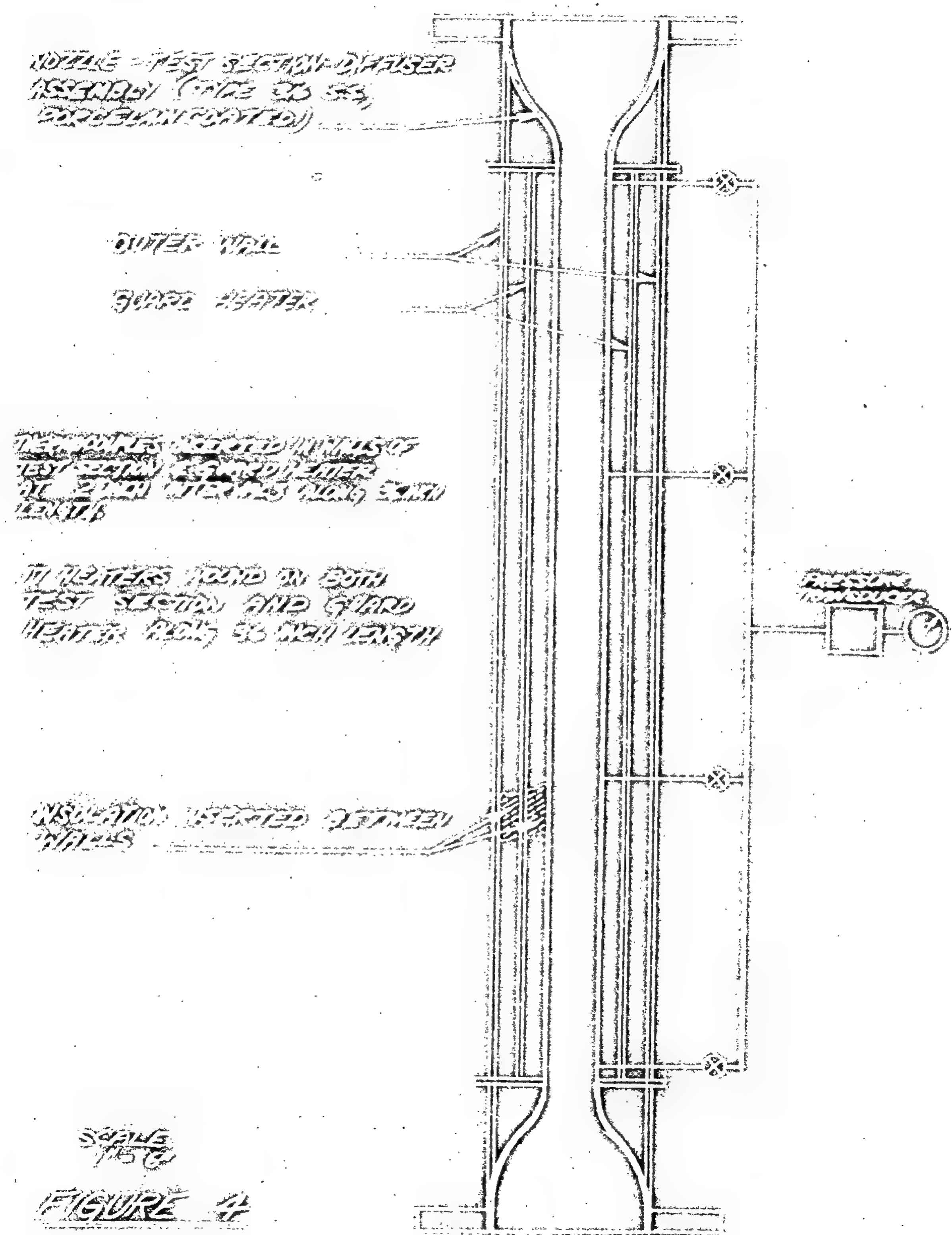


FIGURE 4

guard heater and insulation around the test tube along its entire length, thereby reducing radial conduction to a sufficiently small smount.

The schematic diagram of the test section in Figure 4 indicates the positioning of the inner tube, guard heater, and outer wall. A nozzle increases the Reynolds numbers from the 6 inch diameter pipe to the test tube, and a diffuser is used at the exit to decelerate the flow with minimum pressure loss.

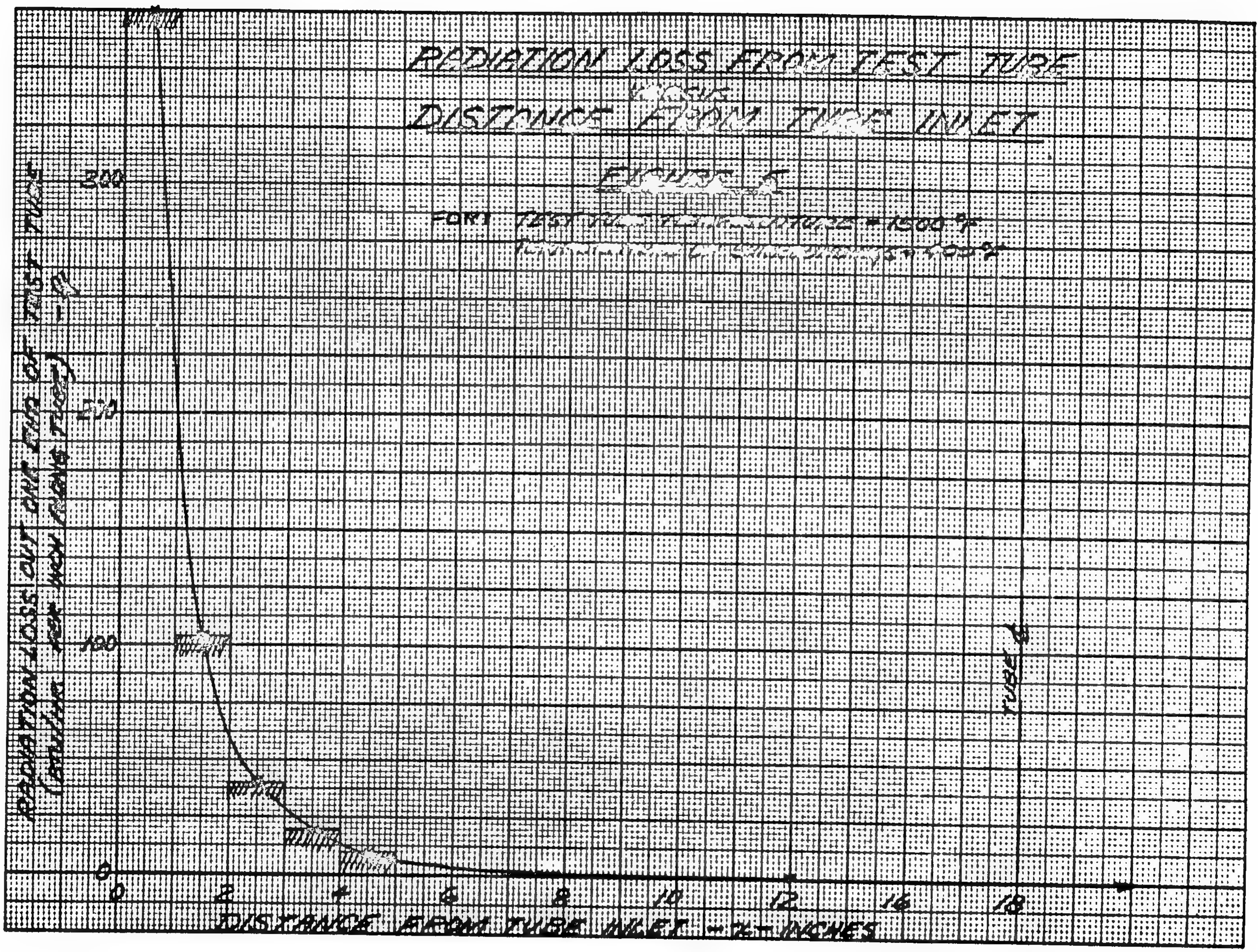
Heating elements attached to the outer surface of the 2 inch test tube will be capable of keeping the inside wall temperature along the three foot length at any desired value between 400°F and 1500°F. Similar heating elements will be installed on the guard heater tube surrounding the test tube. Insulating material between the walls will hold radial conduction losses to a minimum value limited only by the ability to hold the guard heater and test tube temperatures at the same value.

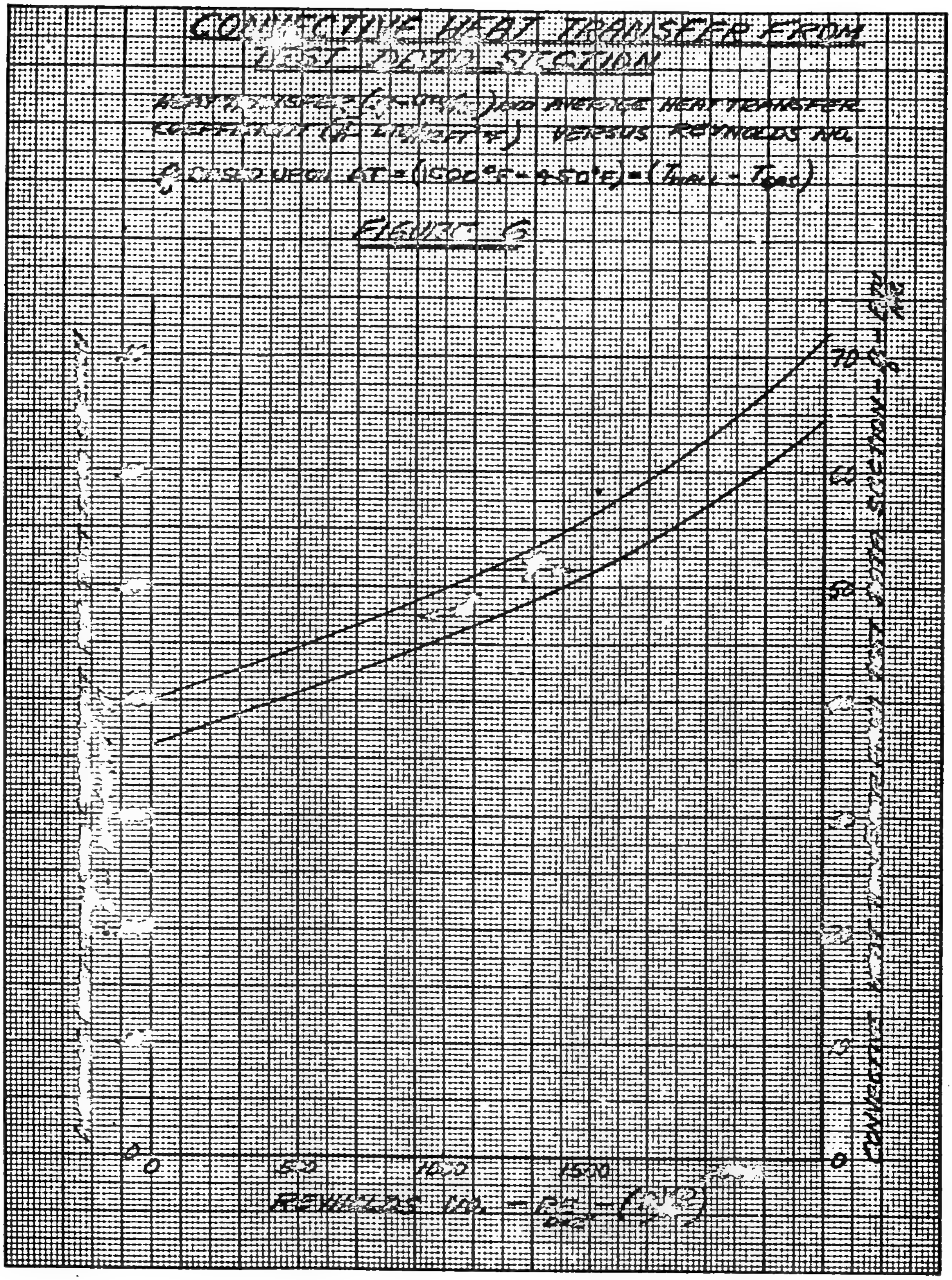
Calculations for the different heat losses out of the test data section are shown in Appendix B2. These calculations are made for the highest wall temperature (1500°F) and an entering iodine temperature of 450°F. The radiation heat loss from the middle one foot section is approximately 3 Btu/ hr. out each end. The axial conduction heat loss out of this middle foot should be zero because the end parts of the test tube will be at the same temperature.

The axial conduction loss out of each one foot end section of the test tube is approximately 420 $^{Btu}/hr$. The radial conduction loss to the guard heater is negligible.

The radiation loss out of the test tube as a function of distance along the tube is plotted in Figure 5 on the following page. This plot is for a test tube wall temperature of 1500°F radiating to surfaces at 400°F. Since the radiant heat transfer is proportional to the temperature to the fourth power, it drops quickly as the test tube wall temperature is reduced. The graph of radiation heat transfer vs. distance along the tube makes it obvious that considerably more power will have to be put into the heaters at the ends of the test section to keep the wall temperature at 1500°F.

The convective heat transfer to the iodine vapor in the test tube is the quantity which must be measured accurately. This value must be large compared to the other heat transfer losses. The convective heat transfer from the test tube data section to the iodine vapor is plotted versus diameter Reynolds number in Figure 6 on page 23 for a wall temperature of 1500°F and an entering gas temperature of 450°F. The average inside heat-transfer coefficient for this section is also shown on the graph. Sample calculations for the results used to make these plots are shown in Appendix B2. All calculations are made for pure I_2 vapor. The possible effect of dissociation is presented


RADIATION LOSS FROM TEST TUBE
DISTANCE FROM TUBE INLET
TUBE
0
100
200
300
0
2
4
6
8
10
12
16
18
DISTANCE FROM TUBE INLET — X — INCHES
RADIATION LOSS OUT ONE END OF TEST TUBE
(BTU/HR PER INCH ALONG TUBE) — Q


CONVECTIVE HEAT TRANSFER FROM
TEST PLATE SECTION
AND AVERAGE HEAT TRANSFER
VERSUS REYNOLDS NO.
FIGURE 6
70
60
50
0
0
500
1000
1500

later. The convective heat transfer in the test data section calculated for the given case is between 40 and 70 $^{Btu}/_{hr}$. The calculations for the heat transfer rates at low Reynolds numbers are not exact because the temperature difference used is approximate. The actual temperature difference will be somewhat smaller than that used. Consequently the actual heat transfer at low Reynolds numbers, before considering dissociation effects will be less than that shown in Figure 6. Although the absolute value of the predicted convective heat transfer is not exact, its magnitude is considerably larger than that of the radiation and conduction losses. Consequently reliable data and results can be obtained from this test section.

The effect of dissociation on the heat transferred to the iodine vapor should be to increase it. The heat of dissociation for iodine, the heat of reaction for $I_2 \rightarrow 2I$, is approximately 37,000 calories per gram mole or 260 $^{Btu}/_{lb}$. Consequently more heat must be added if dissociation occurs. An accurate theoretical prediction of the effect of iodine dissociation on heat transfer is beyond the scope of this thesis. An approximate calculation of this effect is presented in Appendix B3. This calculation is made for a test tube wall temperature of 1500°F, a free stream iodine temperature of 450°F, and an iodine pressure of 0.01 atmospheres. The calculation is made on the basis of a report by David Altman and Henry Wise (2). The heat transfer with dissociation

is predicted to be about 10 times the heat transfer that would occur if there wereno dissociation. The accuracy of this calculation is questionable, but it shows that the effect of dissociation on heat transfer should be large enough to be experimentally measurable.

The methods for obtaining different amounts of dissociation in the experimental apparatus are presented in Section IV.

An estimate of the total power input to the test section, including test tube and guard heater was made. This calculation is shown in Appendix B2. The maximum total power requirement is approximately 1 KW. Of this the major portion supplied is to the test tube ends.

B. CONSTRUCTION AND INSTRUMENTATION

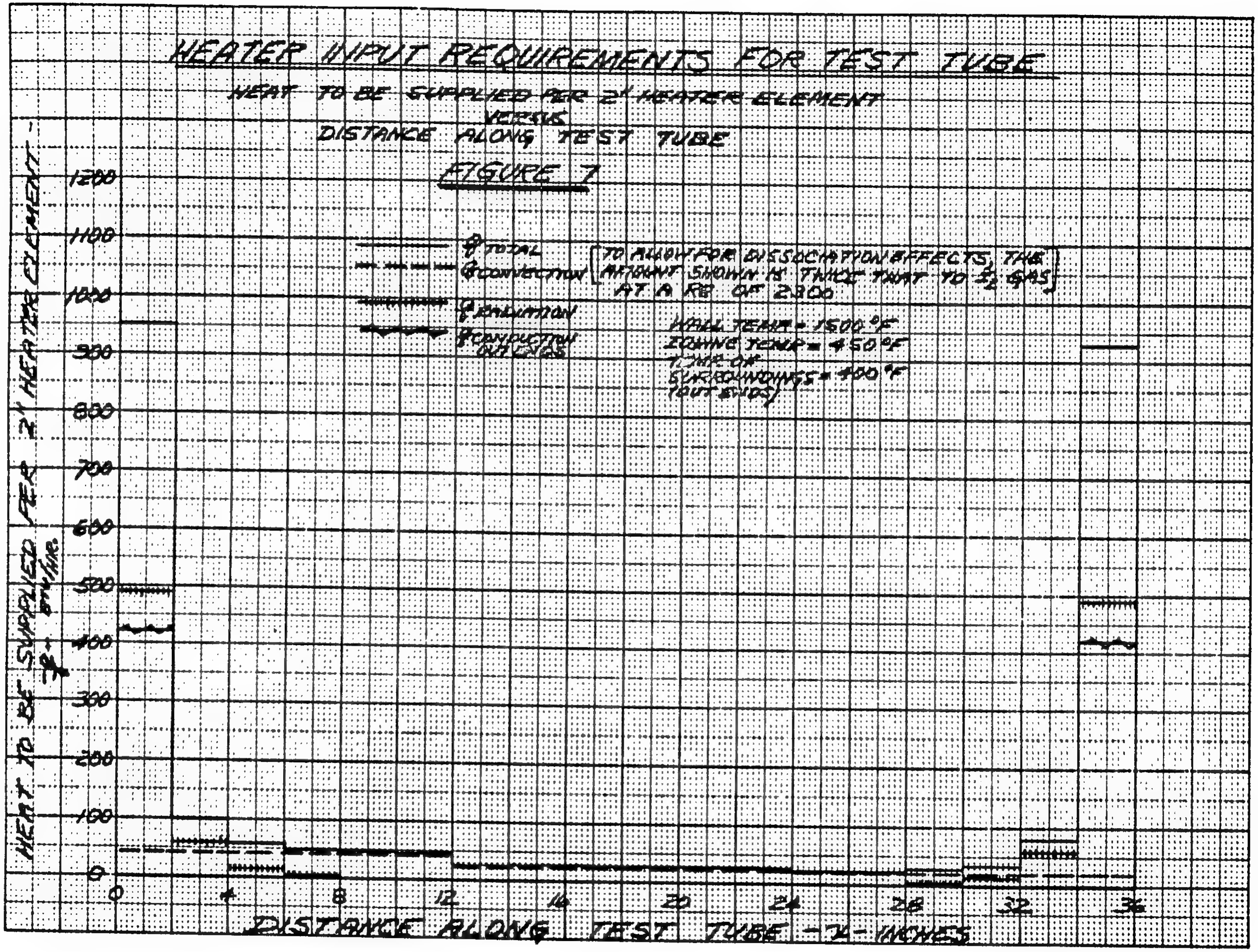
Once it was decided that the test section configuration would make meaningful heat transfer measurements possible, the next step was to accomplish the physical construction and instrumentation of such a test section.

For reasons that are explained in Section III, it is necessary that all surfaces of the test section that may be in contact with iodine vapor be porcelain coated. Because the temperature of the test section must go as high as 1500°F, the Bettinger Corporation, a porcelain coating company in Milford, Massachusetts, recommended that the material for the test section be type 316 stainless steel. Accordingly the two inch diameter test tube and the nozzle

and diffuser for the test tube have been obtained in this material. Two standard 6 x 2 inch stainless steel reducers were purchased and will be machined to improve the inside contours for use as a nozzle and a diffuser. The nozzle and diffuser will be welded to the test tube with a 100% weld. The inside surface will then be machined to remove any irregularities that would disturb the flow in the test tube.

The guard heater, a five inch diameter steel tube, must be cut in half along its length because it cannot be installed around the test tube until the test tube, with nozzle and diffuser attached, is porcelain coated. An assembly drawing of the test section including the guard heater and outer shell, is presented in Appendix C1. The outer shell, which is to be kept at the same temperature as the 6 inch tunnel piping (250° - 450°F) is to be assembled in the same manner as the guard heater.

After the test tube is porcelain coated, nichrome heater wires will be wound around the tube. These heater wires will be in spiral grooves or threads machined in the outside of the 2 inch diameter test tube. Because of the varying power requirements needed along the test tube, separate heater elements, each covering a 2 inch length of the tube, must be installed. The maximum power requirements needed are plotted versus distance along the tube in Figure 7 on the following page. The magnitude of the heat transfer to the gas is shown by two lines, one for the value expected based on I_2 properties and without making allowance for


HEATER INPUT REQUIREMENTS FOR TEST TUBE
HEAT TO BE SUPPLIED PER 2" HEATER ELEMENT
VERSUS
DISTANCE ALONG TEST TUBE
FIGURE 7
q TOTAL
q CONVECTION
q RADIATION
q CONDUCTION OUT ENDS
[TO ALLOW FOR DISSOCIATION EFFECTS, THE AMOUNT SHOWN IS TWICE THAT TO H2 GAS AT A RE OF 2300]
WALL TEMP = 1500 °F
ZONING TEMP = 450 °F
TEMP OF SURROUNDINGS = 400 °F (OUT ENDS)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
4
8
12
16
20
24
28
32
36
HEAT TO BE SUPPLIED PER 2" HEATER ELEMENT - q - BTU/HR.
DISTANCE ALONG TEST TUBE - X - INCHES

dissociation, and the other allowing an additional 100% for dissociation effects. The power to each separate heater installed along the test tube will be controlled with a variac.

The heater wires for the guard heater will be installed and controlled in the same way.

Since it is desired to maintain the test tube and guard heater tube at the same temperature during experiments, thermocouples will be installed in the walls of the test tube 180° apart and at two inch intervals along the tube. Thermocouples will be installed in similar positions on the inside wall of the guard heater tube. During experiments the power input to the separate heaters can be adjusted until the test tube and guard heater tube are the same temperature at all positions.

The outside surfaces of the test tube and guard heater tube will be porcelain coated before the nichrome heater wires are wound around them. This coating will provide electrical insulation between the wires and the tubes. An expensive alternative solution would be to purchase a type of insulated heater elements. The cost of these alternative "Aeropak" heaters would be approximately $1200 for use on both test tube and guard heater.

The thermocouples installed in the test tube walls will be inserted into small holes drilled from the outside to within approximately 0.05 inches of the inside surface.

"Sauerizing" compound, a high temperature cement, will be applied over the whole outside surface of the tube. The

thermocouples and heater wires will be permanently held in place by this cement. The thermocouple leads and the heating element leads will be covered with small porcelain tubes to prevent any possible contact with the guard heater or outer shell. The location of these protective insulating tubes can be seen in the test section assembly drawing. In the drawing the upper row of tubes contains the thermocouple leads and the lower row of tubes contains the heating element leads.

The thermocouples for the guard heater do not have to be imbedded in the tube wall. They are attached to the inner surface of the tube wall and led out through the guard heater and outer shell in small porcelain tubes. The leads for the guard heating elements are led out past the outer shell in the same type of tubes.

Once all the lead wires and tubes are in place "Sauerizing" compound will be applied around the guard heater to fix them in position.

Further test section instrumentation includes four pressure taps at distances of 1, 12, 24, and 35 inches along the test tube. Since the iodine vapor will be in contact with all the surfaces from the pressure tap to the pressure transducer used to measure the pressure, it is necessary that these surfaces be corrosion resistant. Consequently the part of the attachments out to the outer shell must be porcelain coated. To accomplish this, the stainless steel tube above the pressure tap hole must be welded in place before porcelain coating to assure that all inside surfaces are protected.

This stainless steel tube must be at least 4 inches long to get out past the outer shell because other corrosion resistant materials such as glass or teflon can not be used at temperatures near 1500°F. A test piece coated by the Bettinger Corporation showed that a $^{3}/8"$ inside diameter tube welded above a $^{1}/16"$ diameter hole in a piece of 2 inch diameter pipe can be coated satisfactorily. The outside end of the attached tube is tapped with a $^{1}/4"$ pipe tap so that a teflon valve can be attached to it. This will be done for each of the pressure taps. The other ends of the teflon valves are fitted with swage-lock connections. A manifold made of glass tubing is then used to connect these valves to a pressure transducer. This design facilitates the use of one pressure transducer for all pressure measurements.

The temperature of the gas stream before and after the test section is measured with shielded thermocouples. These thermocouples are inserted through attachments welded to the walls of the 6" pipe immediately preceeding and following the test section.

The test section unit, when it is assembled,will support the portion of the tunnel above it. The nozzle and diffuser will be connected to the six inch diameter pipe sections with flanged unions containing teflon seals. It will be necessary to install cooling coils around the nozzle and diffuser near these connections to assure that the temperature of the seals does not exceed 450°F. By controlling the flow rate of the coolant through the coils, the wall temperature near the seals can be kept at a safe temperature.

III. CLOSED-LOOP TUNNEL DESIGN

A. INTRODUCTION

The decision having been made to concentrate further work on the closed loop tunnel, it was necessary first to determine the size of the apparatus and of the individual components to be included. In designing the tunnel compromises had to be made between proposed ideas which might give the best results and other possible solutions which would not be ideal, but which were more practical economically. The design decided upon is presented here and some of the possible alternatives are discussed. A schematic figure of the tunnel is shown on page 13, and an assembly drawing of the main apparatus is included in Appendix C2.

Most of the apparatus is constructed of six inch diameter porcelain coated steel pipe. The test section is two inch stainless steel porcelain coated pipe, and the fan for driving the Iodine vapor is installed in a twelve inch reducing tee. The apparatus is approximately ten feet high and three feet wide.

B. LOOP PRESSURE DROP AND FAN CHARACTERISTICS

To make the proposed experiments it is desired to have laminar flow in the test section. Consequently the diameter Reynolds numbers in the test section must be restricted to 2300 or less. The design of the test section, discussed previously, was determined by what is necessary

to get meaningful data and by the feasibility of construction. This resulted in the requirements of a certain iodine flow rate range, presented in Table II, page 8.

The possible mechanisms for driving the flow of iodine vapor are natural convection or the use of a fan or compressor. The flow rates and Reynolds numbers desired in the test section could not be obtained by natural convection. The use of a compressor, either axial or centrifugal, is eliminated by economic factors and construction difficulties. Since iodine vapor is quite corrosive, common steels cannot be used inside such an apparatus. Even if it were possible to coat a compressor with porcelain or some other corrosion resistant material, the cost would be prohibitive. Consequently the machinery for driving the iodine vapor is limited to a fan.

Fans are generally designed to produce relatively high flow rates for low pressure drops across the fan. For the low flow rates planned, the fan could therefore produce only a small pressure rise. For this reason the pressure drop the iodine undergoes in circling the loop, due to friction, elbows, etc., must be kept at a minimum.

In calculating the pressure drop characteristics of the apparatus, some simplifying assumptions are made. All calculations are made for I_2 vapor, neglecting any changes in average properties due to dissociation. The properties of iodine are taken at two average temperatures,

approximating the real case where the temperature in steady state operation will vary with position in the loop. The flow is assumed laminar everywhere inasmuch as the Reynolds number in the minimum area test tube is equal to or below 2300.

The pressure drop characteristics for the final design are shown in Figure 8 on the following page. The pressure drop is converted to inches of water at standard air density to compare it to the fan characteristics. The curves shown in the figure are made for an average temperature of 1000°F in the test section and 500°F in the rest of the loop, approximating the maximum running temperatures. These maximum values are used because they give the maximum pressure drop for a given velocity and Reynolds number in the test section. This is because for a constant Reynolds No., as the temperature is increased, the viscosity increases and the density decreases, consequently the head loss increases.

The head loss (pressure drop) in inches of water is:

$$H_e = \frac{12\rho}{\rho_{H_2O}} \frac{V^2}{2g} f\frac{L}{D} \propto \rho \cdot V^2 f \frac{L}{D} \propto \rho \cdot V^2 \frac{1}{Rey} \frac{L}{D}$$

$$\propto \left(\frac{\rho V D}{\mu}\right)^2 \frac{1}{Rey} \frac{L}{D^3} \frac{\mu^2}{\rho} \propto Rey \frac{L}{D^3} \frac{\mu^2}{\rho}$$

A sample calculation for the pressure drop around the loop is presented in Appendix B4.

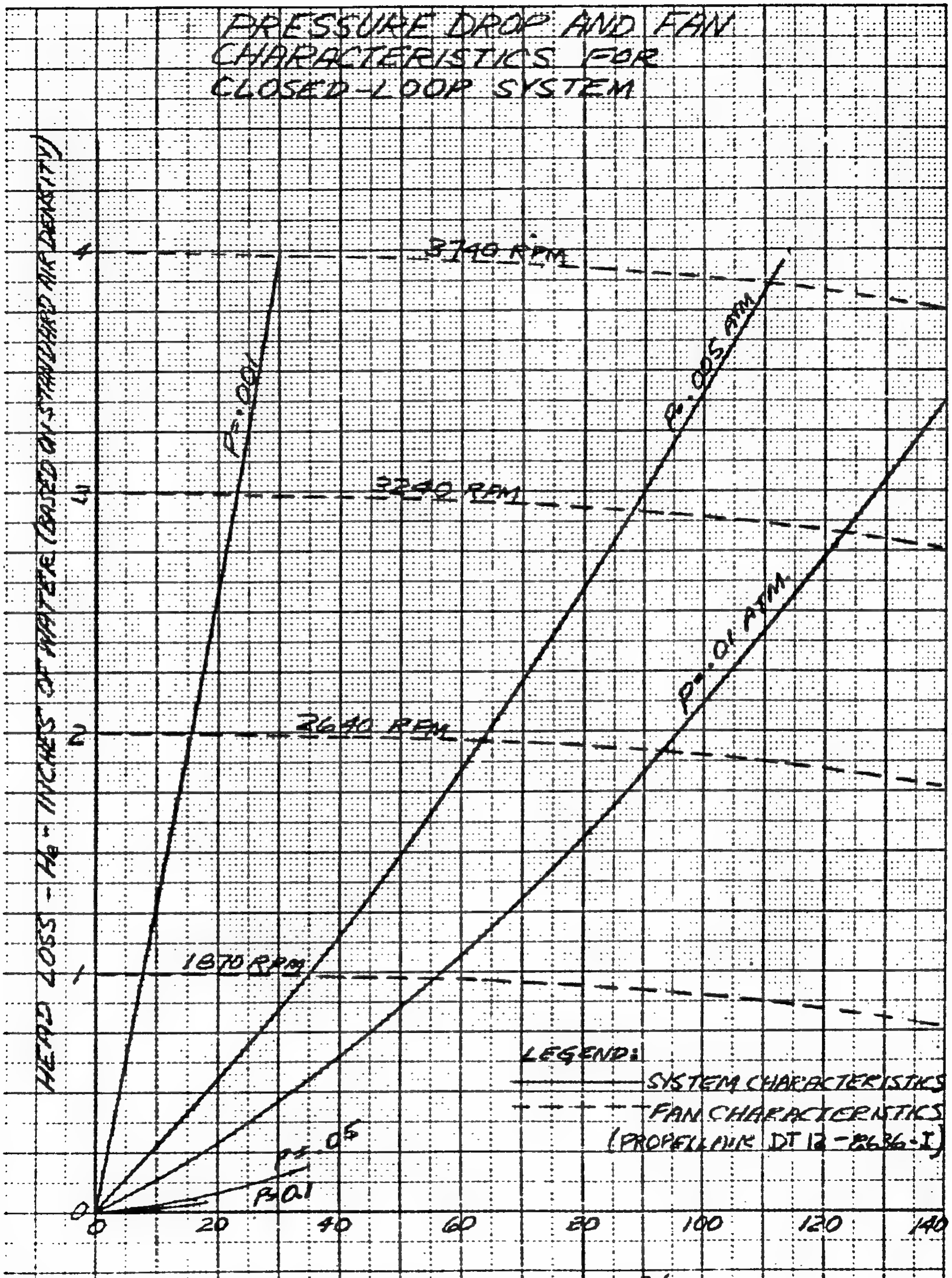

PRESSURE DROP AND FAN
CHARACTERISTICS FOR
CLOSED-LOOP SYSTEM
HEAD LOSS - H_e - INCHES OF WATER (BASED ON STANDARD AIR DENSITY)
3740 RPM
3240 RPM
2640 RPM
1870 RPM
P=.001
P=.005 ATM
P=.01 ATM
P=.05
P=0.1
LEGEND:
SYSTEM CHARACTERISTICS
FAN CHARACTERISTICS
(PROPELLAIR DT 12-8636-I)
0
1
2
3
4
0
20
40
60
80
100
120
140
VOLUME FLOW RATE - Q - FT³/MIN

FIGURE 8

The fan chosen for the apparatus is a Propellair pressure type fan, number DT 12-8G36-I, obtainable from the Wolverine Equipment Company in Cambridge, Mass. The characteristics of this fan are shown in Figure 8 with the loop pressure drop characteristics.

The decision to make most of the apparatus six inch diameter and have a twelve inch diameter fan was made as a compromise between lowering the system pressure drop by going to larger diameter piping and having to go to a larger fan. As it is now, the range of operation is limited somewhat at a system pressure of .001 atmospheres. The maximum test section Reynolds Number attainable at this pressure is about 150 rather than 2300. At a pressure of .005 atmospheres, however, the full range of test section Reynolds Numbers up to 2300 can be obtained.

C. MATERIALS SELECTION

The choice of materials for the apparatus is limited by the corrosive properties of iodine vapor. Previous research by Eastman (1) essentially reduced the choice for the main tunnel components to one between porcelain coated steel and glass. Other materials were eliminated because they are either prohibitively expensive, not corrosion resistant, or they present extremely difficult construction problems. For the final design porcelain coated steel was chosen rather than glass for the reasons discussed on the following page.

The test section could not be glass because glass cannot stand temperatures up to 1500°F. The fan assembly has to be steel for strength and construction feasibility. Glass is not used in the rest of the apparatus, except for the flow meter section, because of the difficulties that would arise in trying to make attachments for temperature and pressure measurements. Even if a glass blower could make attachments to Pyrex pipe, the strength of the glass would be decreased in that area. With porcelain coated steel, any attachments can be welded on before the coating is applied, and it then protects the joint and attachment from corrosion.

A number of test pieces have been porcelain coated and tested to: a) determine porcelain's resistance to iodine; b) learn which steels and what types of machined surfaces can be coated; and c) obtain porcelain coated surfaces for conducting experiments with different vacuum seal arrangements. The porcelain coating has been done by the Bettinger Corporation in Milford, Mass. From their experience they are able to recommend certain types of steel and aluminum that may be coated, in preference to others that present difficulty. If the carbon content of the steel is too high, the porcelain coating will not adhere satisfactorily because of carbon emission at the steel surface during the high temperature baking process. Tests have shown that steel pipe and fittings with ASTM A234

specifications can be coated with a porcelain that is good for temperatures up to 450°F, while cast iron is definitely to be avoided. For the test section where the temperature will be as high as 1500°F, type 316 stainless steel must be used with a different coating.

Sharp edges must be broken on pieces to be porcelain coated because the coating will not adhere to such edges during the baking process. Any welding on pieces to be porcelain coated must be done on pieces of similar composition with a welding material that matches.

A test container consisting of a four inch pipe sealed at one end and bolted closed with a blind flange at the other end, porcelain coated on all inside surfaces, was used for conducting several material and sealing tests. It was filled with and subjected to iodine vapor at 400°F for 36 hours and the porcelain coating was not affected.

D. SEALING MATERIALS AND CONNECTIONS

Possible seals for the connections in the apparatus are limited to materials that will withstand temperatures in the 400 - 450°F range and resist corrosion or attack by iodine vapor. Most of the common rubber and metal gasket materials to not stand up to iodine, particularly at these higher temperatures.

Two materials that had been recommended for gaskets were Teflon and Viton, both manufactured by duPont. No data on corrosion resistance to iodine was available for either of these materials. Viton is a more resilient material than

Teflon and would therefore be a better gasket material. Teflon is more plastic and "cold flows". Both Teflon and Viton were subjected to iodine vapor in test piece #1 at 400°F for four hours. The Viton, apparently of two different types, was noticably attacked by the iodine. The volume of the flat piece increased and its surface was attacked, while the Viton "O" ring disintegrated. The Teflon became discolored (from white to light brown) after the four hours but there were no noticable changes in its physical properties. Additional Teflon pieces were subjected to iodine at 400°F for the longer period of thirty-six hours. This Teflon was discolored to a deeper brown than that subjected to iodine vapor for only four hours, but there were still no other noticable changes. A picture of the Teflon and Viton pieces subjected to the iodine vapor is shown in Figure 9 below. On this figure the corrosive effect of iodine on stainless steel is also shown.

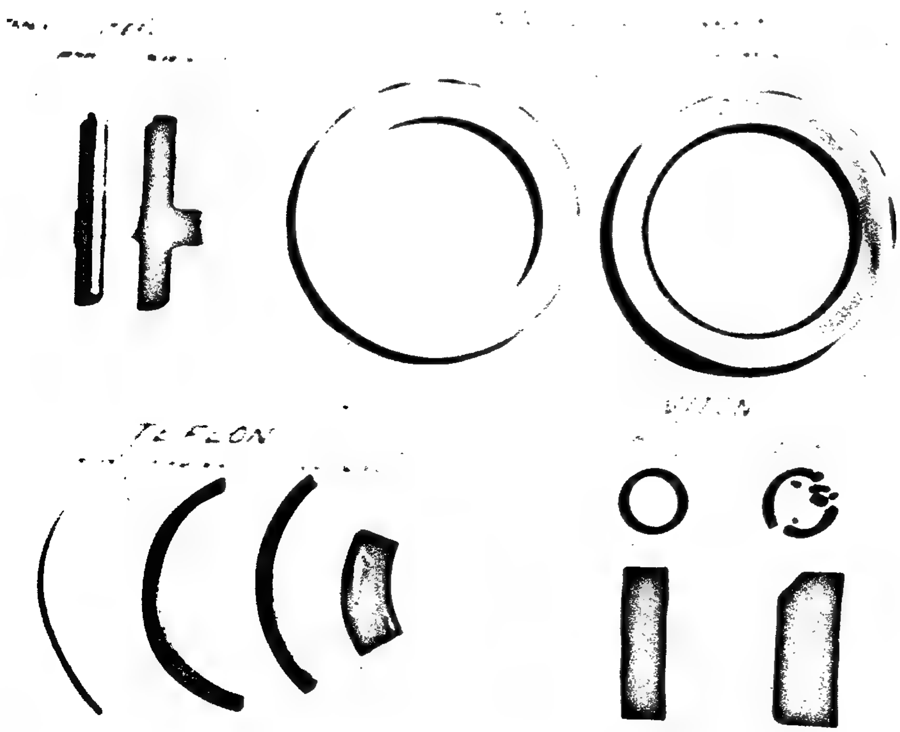


Figure 9

Test Results

On the basis of these tests, Viton could not be used as a sealing material. With regard to the Teflon, it was not known whether the iodine reacted with the Teflon or if it was simply absorbed, since other than the discoloring there were no other noticable changes. Several chemical analysts were contacted but none could definitely state what had occurred or could assure that he could determine it through analysis. Professor Brown spoke with two different people from duPont who both believed that the iodine was absorbed in the Teflon without chemical reaction. These opinions were supported by statements concerning the bonding energy between carbon and fluorine and the atomic structure of Teflon, but no tests are known to have been made to support these opinions.

In ordering Teflon duPont recommended that premium sheet from Teflon 7, or at least Teflon 6 or 7 be specified. Teflon 7 has the minimum void content of any Teflon. The specifications for premium Grade A Teflon require zero penetration for a porosity test.

The Teflon that had been tested as described prior to this knowledge was in the form of commercial gaskets and an "O" ring where it is suspected that reprocessed Teflon was used in the manufacture for economical reasons. Consequently the tested samples were probably not premium Teflon 7. No premium Teflon 7 has yet been obtained for test purposes.

Two types of seals and connections have been used in the design of the tunnel. Wherever possible High Voltage

Corporation vacuum connections are used. These connections are made by the High Voltage Engineering Corp., Burlington, Mass., specifically for vacuum applications. They eliminate any welding at the joints, simplify alignment and assembly, and incorporate the use of an "O" ring seal between the two pieces of pipe to be joined. The "O" ring is positioned by two retaining rings. The two halves of the flange which are bolted together cause the "O" ring to be compressed between the two pipe ends being connected. A test unit, was constructed to test this type of seal.

At several of the connecting positions on the tunnel, however, it is not feasible to employ the High Voltage connectors. This occurs at the reducing elbow and reducing tee connections. Machining required on the six inch ends of these bulky pieces, to allow such a connection, would be difficult and expensive. High Voltage connectors are not produced in the twelve inch sizes needed for the large diameter connection. At these joints, therefore, flat gaskets will be compressed between standard ASME weld neck or slip-on flanges. Similar connections are required at both ends of the glass section and the bellows installation.

The gaskets to be used are Teflon envelope gaskets with an asbestos filler. This filler gives the gasket more resiliency than it is possible to obtain with pure Teflon.

Both types of connections have been tested under vacuum at room temperatures and work satisfactorily under these

conditions. The connection using a Teflon envelope gasket was tested at 400°F while in contact with iodine vapor and leakage occurred. A leak was found in a weld in this test piece. Further tests are being made to check other possible causes for leakage, which might include bolt expansion at high temperature and possible to a minor extent diffusion of gases through the Teflon gasket.

E. FAN ASSEMBLY

An assembly drawing of the fan installation is shown in Appendix C3. The fan assembly has been designed to fit into the 12x12x6 steel reducing tee. The fan blade and the portions of the shaft and tee in contact with iodine vapor will be porcelain coated. In designing the fan it was necessary to protect the bearings from the iodine vapor and to incorproate a seal that will prevent leakage and thereby contamination of the iodine vapor. The bearings are protected from the iodine vapor by a double seal. This seal allows the bearings to operate in air under lubrication at atmospheric pressure. If one of the bearings were between the seals, it would have to work in a vacuum where iodine might be present.

The double seal arrangement designed to prevent leakage and contamination of the iodine vapor inside the tunnel consists of two different seals. The pressure between them will be maintained at a value equal to or less than the pressure of the iodine vapor in the apparatus. By maintaining this pressure at such a level, the seal in contact with the iodine vapor only has to work against a small

pressure differential or none at all. This will minimize any leakage and assures that leakage, if any, is iodine outward, thereby preventing contamination of the tunnel's iodine atmosphere. If leakage occurs through this seal arrangement at any noticeable rate when the apparatus is in operation, make-up iodine will have to be introduced at the proper rate through the iodine inlet from the boiler. If no other leaks exist in the tunnel, iodine make-up could be regulated to maintain the tunnel pressure at the desired constant value.

The materials that can be used for use as shaft seals against iodine vapor if little or no contamination is to be allowed are limited to Teflon, ceramics, and carbon. The seal chosen for contact with the iodine vapor has a Teflon sealing element. Different commercial seals that have ceremic on carbon sealing surfaces all have some rubber or Viton that make them impractical for use with iodine vapor. The Teflon seal in contact with the iodine is not designed to work against a pressure difference. The outer seal in the assembly is designed to work against a pressure difference but will not stand up in iodine vapor. The double seal designed in this manner with a vacuum pulled between the seals should reduce leakage and contamination to a minimum. Otherwise a special seal would have to be designed and constructed. Before any further time and expense are expended, the present fan assembly should be built and tested.

The fan shaft will be connected to a variable speed motor to provide iodine flow control.

F. FLEXIBLE COUPLING

At some point in the tunnel a flexible coupling is necessary because thermal expansion of the different parts of the tunnel will be unequal. The test section is made of 316 stainless steel and its temperature will reach 1500°F. The other parts of the tunnel, mostly low carbon steel, will not exceed a temperature of 400°F. The thermal expansion coefficient for the 316 stainless steel is higher than the expansion coefficient for low carbon steel. Consequently the side of the apparatus containing the test section may expand approximately 0.40 inches more than the other side. The calculation for this is shown in Appendix B5.

To compensate for the difference in expansion, a Teflon expansion joint is to be installed in the apparatus. This bellows, made by Resistoflex Corporation, was purchased from John G. Shelley Company in Wellesley, Mass. The expansion joint is made of Teflon 6, has a travel of plus or minus $1^1/8$ inches, and is designed to operate in a vacuum system at temperatures up to 450°F.

The expansion joint has three travel limit bolts to limit expansion. When the expansion joint is installed in the apparatus as shown in Appendix C2, springs will be installed around the limit bolts and between the flanges.

These springs will reduce the bending moment on the connections in the top of the apparatus which exists due to the weight of the piping.

G. PRESSURE MEASUREMENT

Pressure measurements in an iodine atmosphere cannot be made with ordinary manometers because the iodine will chemically react with any usable liquids. The iodine vapor must in addition be kept at a temperature between 200°F and 400°F in the measuring apparatus to keep it a vapor, the exact value of temperature depending upon the system pressure. Helicoid Gage Division of American Chain and Cable Company makes a mechanical gage with a Teflon diaphram but at 400°F the diaphram is not sensitive enough to give accurate readings for the low pressures involved.

A pressure transducer with a metal diaphram and an electrical pickup at present seems the only alternative. The Dynamic Instrument Company in Cambridge, Mass. makes a transducer, model PT 25, with a range from 0 - 15 psia. This transducer can be made with a 347 stainless steel diaphram, which it may be possible to cover with a thin sheet of Teflon. Otherwise the stainless steel diaphram will have to be in contact with the iodine vapor. Either way the system is not ideal, but it is the best solution yet available. B. J. Electronics of Santa Ana, California, have indicated they are able to deliver a transducer that will hold up under iodine and work in the desired pressure range for $700, but have not yet supplied details.

The locations where pressure measurements will be made are shown in Figures 2 and 4 on pages 13 and 19. The pressure is measured at different points in the test section and in the six inch section immediately below the flow meter.

H. TEMPERATURE MEASUREMENT

The temperature of the iodine vapor in the apparatus can be measured at five different locations. The thermocouples used to measure the vapor temperature must have radiation shields, because the iodine vapor temperature will generally be different from the surrounding wall temperature, by as much as a few hundred degrees Fahrenheit in some locations.

The shielded thermocouples, which will be purchased commercially and either porcelain or Teflon coated, are installed in the apparatus through one and one-half inch diameter outlets welded to the six inch pipe at several locations indicated in Figure 2, page 13. This method of construction permits the thermocouples to be installed after the bulk of the apparatus is porcelain coated, assembled, and tested.

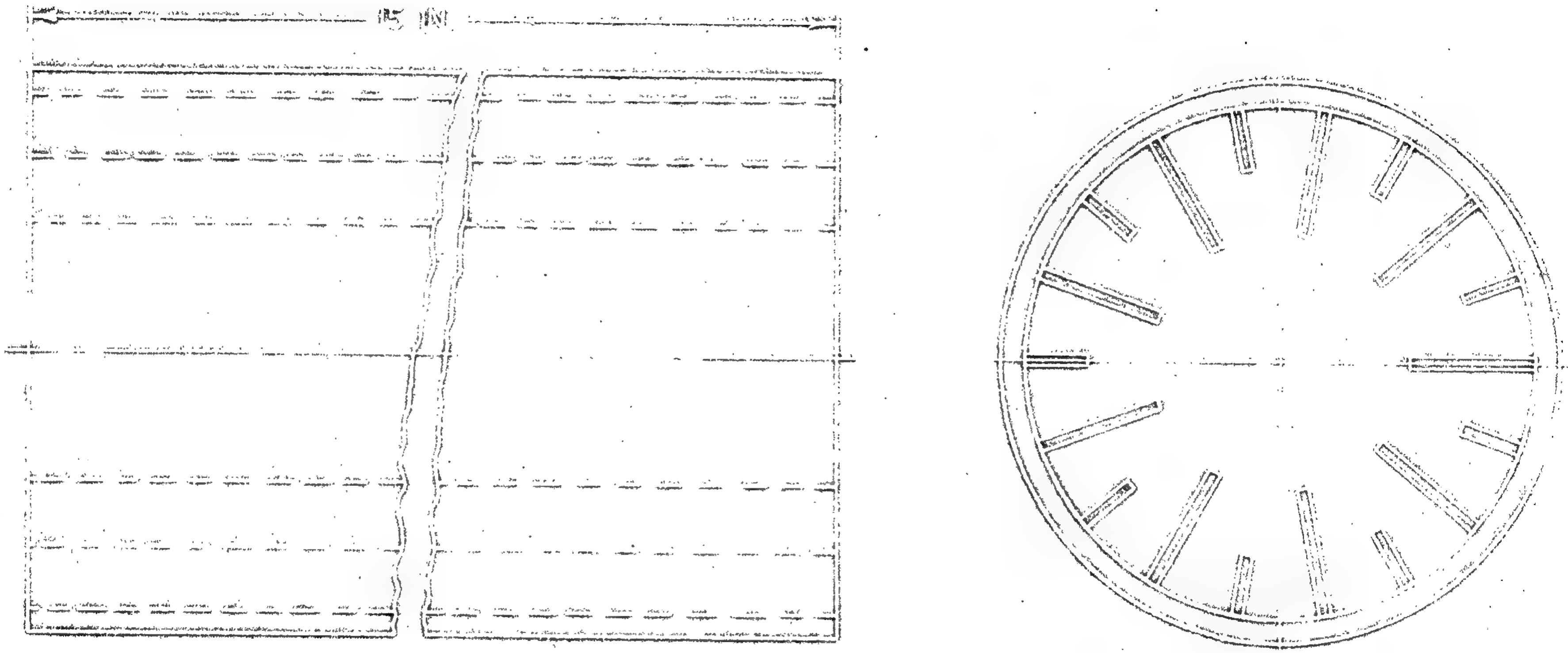
I. COOLING SECTION

Heat transfer calculations for the test section show that the temperature of the iodine vapor leaving the test section may be as high as 1100°F. The recirculating iodine vapor must be cooled to approximately 400-450°F before it re-enters the test section. The length of six inch diameter

pipe with a wall temperature of 400°F required to cool the iodine vapor to 950°F is longer than that installed in the apparatus. Consequently more heat transfer surface is necessary for the high Reynolds No. flows conducted at high pressures where wall temperature must be kept at 400°F. The most effective way to obtain this with the least amount of pressure drop is to install an internally finned section with longitudinal fins as close to the test section exit as possible.

The calculations showing the need for a finned section are shown in Appendix B6. Because by far the largest resistance to heat transfer is between the iodine vapor and the inside surface, the fin effectiveness is almost 100%. The fins are to be welded in the positions shown in Figure 10 on the following page to the inside of the fifteen inch long six inch diameter pipe before porcelain coating.

When the gas is being cooled, the inside surface temperature of the pipe must be kept above the value at which iodine will solidify or liquify for the given tunnel pressure of operation. This requirement along with the fact that the pipe's outside heat transfer coefficient is high relative to the inside coefficient means that the outside of the pipe must be heated, or the wall temperature would never reach the required value. This will be done using heating tapes wound around the outside of the tunnel piping, and insulation applied around them.



SCALE ½ SIZE

FIGURE 10 - COOLING SECTION FOR CABLE 1 IN.

BEST AVAILABLE COPY

If experiments show that the heat transfer due to dissociation is greater than expected, preliminary tests can be conducted at test tube temperatures below the 1500°F chosen as a maximum value, or another finned section can be installed in the apparatus immediately below the expansion joint.

J. FLOW MEASUREMENT

In order to get meaningful data and results from the apparatus, it is necessary to be able to determine the flow rate of iodine vapor. A number of different flow meters have been considered for the apparatus.

The fact that the pressure drop around the tunnel is quite small excludes the use of an orifice type flow meter, where a differential pressure measurement is made to determine the flow. The total pressure drop around the tunnel is always less than 0.1 inches of water.[1]

The same difficulty is present with a pitot static tube where a differential pressure measurement must be made. The difference between the stagnation and static pressure of the iodine vapor is equal to or less than 0.01 inches of water depending upon the operating conditions.

[1] When the pressure drop was calculated for comparison with fan characteristics, it was converted to a pressure drop based on standard air density. That is why the values shown in Figure 8, p. 34 are greater than 0.1 inches of water.

A hot wire anemometer to get velocity profiles is impractical because it could not be made of corrosion resistant materials and calibration would be difficult if possible. The readings taken from a hot wire anemometer are not a function of Reynolds number or other dimensionless groups alone. Consequently an anemometer must be calibrated using the same fluid in which it is intended to obtain velocity measurements. This is impractical for iodine vapor.

Flow meters based on the principle of rotometers were eliminated for materials reasons and because of calibration difficulties.

Meters based on the principle of deflection caused by a drag force acting on a part of the meter were considered. The deflecting device would be a spring loaded plate or a plate extending into the flow, acting as a cantilever beam. The drag on the plate is related to the iodine flow rate, the iodine gas properties, and the dimensions of the plate. For a given plate the drag can be shown to be a function of Reynolds mumber, iodine., pressure, and iodine temperature, assuming the perfect gas relationship holds for iodine. The same relationship would hold if another gas were used. Consequently a device of this type could be calibrated with air rather than iodine.

Calculations showed that the drag force on a six by one inch plate normal to the flow is only 10^{-4} to 10^{-7} pounds for flow rates of iodine considered for this apparatus. The weight of a six by one inch steel plate that is 0.001 inches

thick is approximately 10^{-3} pounds. Consequently any deflection of the contilever beam caused by the drag force would be at least an order of magnitude less than the deflection caused by the weight of the beam alone. This fact makes a deflection device of this sort impractical as accurate measurements could not be obtained. Any spring loaded deflection device would have the same difficulty associated with it, namely that the load due to drag would be negligible compared to the static load due to the weight of the device.

The drag forces on a vane type anemometer would be of the same order of magnitude as the drag forces on a flat plate. If the device were perfectly balanced its static weight would not be important in the way it is for a deflection device, but a friction force would be present. The friction in the device could not be reduced by bearings or lubrication because no bearings or lubricants are available for use in iodine vapor. Consequently the friction forces in such an anemometer make it impractical.

At the present time no flow meter has been designed for the apparatus. A glass tee has been incorporated for possible use with a visual type flow meter. Either some of the problems associated with the above mentioned types of flow meters must be solved or a more elaborate method of measuring the iodine flow will have to be found.

K. IODINE ENTRY AND EXHAUST

Provisions for filling the apparatus with iodine vapor and later evacuating it are incorporated by installing two

small pipes to the apparatus that can be regulated with Teflon valves. The iodine inlet will be connected to a small furnace where iodine vapor can be generated. This furnace will be filled with a quantity of iodine, evacuated with a vacuum pump, and then heated to produce iodine vapor at a pressure above the desired operating value for the tunnel. This pressure differential will cause the iodine to flow into the previously exhausted apparatus when the inlet valve is opened.

For periodic emptying of the tunnel, the iodine exhaust line from the tunnel will be connected to an iodine vapor trap and then to a vacuum pump. To evacuate the tunnel, hot inert gas (possibly air) will first be added to the low pressure iodine atmosphere to boost tunnel pressure. When the vacuum pump next evacuates the system, the iodine vapor will be condensed in the trap, probably a water cooled condensor, to prevent it from contaminating the vacuum pump and the surrounding air.

L. FLOW STRAIGHTENERS AND SCREENS

In designing the apparatus the installation of flow straighteners and screens before the test section was considered. The flow straightener, comprised of bunched small diameter tubes, would tend to flatten out the velocity profile and assure axial flow. The screens before the test section might reduce the turbulence level of the flow.

After considering the relative value of these additions compared to the difficulties they would present in terms of construction and increased pressure drop, it was decided to eliminate them from the design. The Reynolds No's. in the six inch pipe are quite low and the iodine flow has a relatively smooth approach to the test section. If it becomes necessary to use either the straightener or the screens, they may be installed later in the six inch pipe before the test section.

M. TUNNEL COST ESTIMATE

The proposed list of parts required for the apparatus is shown on Table IV on the following pages. Where it is possible the exact cost of the materials or operation is presented. The parts that have been ordered are indicated with an asterisk.

The proposed total cost is not exact. It is possible that some additional items may prove needed and that some changes may be necessitated.

TABLE IV

CLOSED LOOP TUNNEL COST ESTIMATE

Test Section:

1 -	36" length of 2" SS pipe (Type 316)	31.20*
1 -	36" length of 5" SS tubing	51.33
2 -	6 x 2 concentric ss reducer (Type 316)	142.40*
2 -	specially machined supporting plates	30.00
1 -	36" length of 7" stovepipe	10.00
-	copper cooling coils	5.00
-	Nichrome wire heaters for 2" pipe	100.00
-	Nichrome wire heaters for 5" guard heater	100.00
30-	thermocouples (along 2" pipe)	60.00
30-	thermocouples (along 5" guard heater)	60.00
60-	voltage regulators to control temperatures	600.00
-	insulation (installed between conc. cyl.)	10.00
4-	pressure taps	10.00
4-	Teflon valves	180.00
-	Ceramic tubes porcelain coated	125.00
-	Sauerizing compound	20.00
-	machining of pipes, reducers and pressure taps	120.00
-	welding	100.00
-	porcelain coating	100.00
	Sub Total	$1754.93

Tunnel:

4 -	High Voltage 6" pipe connections	90.00*
2 -	High Voltage machined std. 6" elbows	115.00
1 -	12 x 6 reducing elbow (steel)	170.00
1 -	12 x 12 x 6 tee (steel)	194.00
2 -	12" welding neck flanges	194.00
2 -	6" welding neck flanges	91.08
6 -	6" slip-on flanges	21.36
1 -	6 x 6 x 1 Pyrex reducing tee - 18" long	48.00
1 -	6" expansion joint (Teflon)	55.75*
4 -	Teflon "o" rings to use with High Voltage	137.25*
1 -	12" Teflon gasket	30.00
4 -	6" Teflon gaskets	15.00
-	6" std. steel pipe (ATSM-A234) - 8 feet	32.00
4 -	$1^1/_2$" blind flanges	30.00
4 -	$1^1/_2$" slip-on flanges	15.00
4 -	$1^1/_2$" Teflon gaskets	15.00
-	tubing for iodine inlet and outlet and pressure tap	10.00
3 -	Teflon valves	10.00
-	pipe heating tapes and voltage regulators	135.00
40 -	thermocouples placed along outside surface	1000.00
-	Insulating material for outside covering	80.00
-	quartz heater for Iodine vapor generation	100.00
-	vacuum pump for emptying tunnel	150.00
-	Pressure measuring system	100.00
		300.00

(continued p.54)

TABLE IV (con't.)

	- Flow rate measuring device	200.00
4	- Specially shielded thermocouples	160.00
1	- Covered thermocouple	10.00
1	- Iodine trap	100.00
	- Tunnel supports(materials and assembly)	200.00
	- Machining	200.00
	- Welding	425.00
	- Porcelain coating	300.00
	Sub Total	$4539.44

Fan Assembly:

1	- Fan blade	35.00
1	- shaft	10.00
1	- Garlock Klosure(Teflon)	10.00
1	- Garlock Mechanipak Seal	20.00
2	- Fafnir ball bearings	30.00
	- Miscellaneous steel stock	30.00
	- Machining	100.00
	- Welding	50.00
	Sub Total	$ 285.00

TOTAL $6,579.37

IV. PROPOSED TEST OPERATION AND PRESENTATION OF RESULTS

A. TEST OPERATION

Once the apparatus is assembled and checked out to assure that no leakage occurs, experimental tests can be made. A proposed operational procedure is now presented.

The apparatus should first be evacuated with a vacuum pump and dried out by heating the pipe walls to approximately 400°F. When air and any moisture are sufficiently removed from the apparatus, iodine vapor generated in the boiler may be released into the tunnel. The pressure level in the apparatus can be controlled by controlling the amount of iodine in the apparatus and the mean temperature of this vapor. After the desired amount of iodine is released into the apparatus, the fan should be started to create circulation. The temperature of the test section can then be raised to the desired operating value.

During this procedure care must be taken to keep the wall temperature above the liquification or solidification temperature of iodine corresponding to the iodine pressure in the apparatus. The wall temperature near the seals should not exceed 450°F at any time because the Teflon will start to decompose at temperatures near 500°F.

Steady-state operation for a given run will be achieved when the test section and guard heater, through proper setting of the individual variacs controlling the heaters, are maintained at one constant temperature. At this time

the temperatures of the iodine vapor entering and leaving the test section will be constant.

When steady state operation is obtained, the required temperature, pressure, flow rate, and heating element input data will be recorded.

In collecting data for a number of different runs it will be desirous to change only one independent variable at a time. The independent variables are the test section inlet pressure, inlet temperature, wall temperature, iodine flow rate or Reynolds number, and Prandtl number. The inlet temperature and the Prandtl number will be relatively constant (the inlet temperature because of heating and cooling limitations of the iodine in the six inch pipe, the Prandtl number because its variation with temperature and pressure is small). Consequently the important independent variables are the other three; test section wall temperature, inlet pressure, and flow rate or Reynolds number. In making a set of runs it will be convenient to hold the inlet pressure and the Reynolds number constant and vary the test section wall temperature. Then for the same inlet pressure and a different Reynolds number, obtained by changing the fan speed, another set of runs can be made with varying wall temperatures. This procedure can be continued for a number of different inlet pressures to get a wide range of data.

B. PRESENTATION OF RESULTS

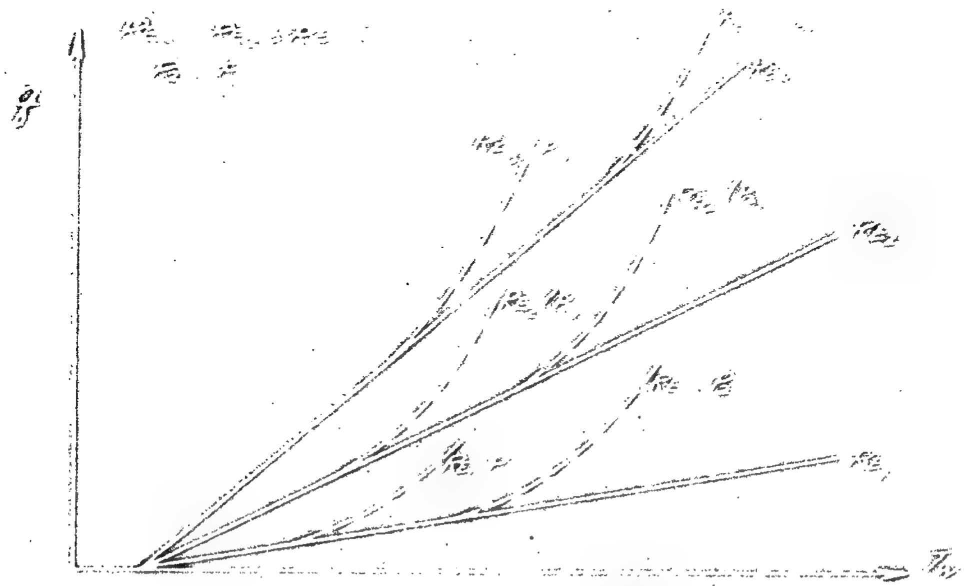
Two possible methods of presenting experimental

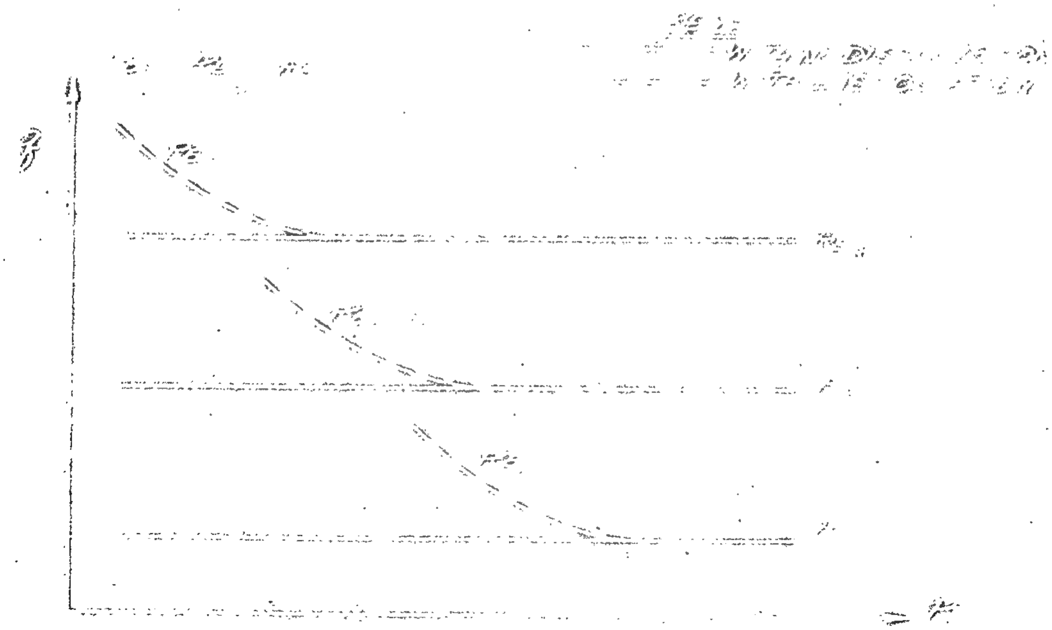
results are shown graphically in Figure 11 (page 58). In Figure 11-a the heat-transfer rate is plotted versus the test section wall temperature with the iodine inlet temperature and the inlet Prandtl number held constant. Figure 11-b is a plot of heat transfer rate versus inlet pressure for constant inlet temperature, constant wall temperature, and constant inlet Prandtl number.

If no dissociation occured, the heat transfer rate for fully developed flow in the given geometry would only be a function of inlet temperature, wall temperature, Reynolds number, and Prandtl number. The inlet pressure would not enter in the functional relationship. For dissociating flow the pressure is an important variable because the amount of dissociation in the test section increases as the iodine pressure is decreased for a given iodine temperature. The effect of dissociation, as previously mentioned, is to increase the heat transfer rate.

The theoretical curves for the plots shown in Figure 11 can be calculated using expressions for laminar flow with a fully developed velocity profile and variable properties. Density variations due to pressure changes along the test section can be neglected because the pressure drop is small, but variations due to temperature change will have to be taken into account.

The solid lines in Figure 11a show qualitatively the expected variation of heat transfer rate as a function of wall temperature and Reynolds number for flow with no dis-





sociation. One curve of q vs. t_w should be obtained for each Reynolds number, independent of pressure. For a given wall temperature, the heat transfer coefficient and consequently the heat transfer rate increase as the Reynolds number increases. The dashed lines in Figure 11-a show the effect of pressure on heat transfer rate as dissociation occurs. When dissociation occurs the heat transfer rate for a given Reynolds number increases. Dissociation effects occur at a lower wall temperature for lower Reynolds numbers because the iodine temperature in the test section increases more at low Reynolds numbers (flow rates) even for lower heat transfer rates. This fact as shown in the sample calculations for the cooling section in Appendix B6. The dissociation effects start at lower temperatures as the pressure is decreased (see Figure 12 in Appendix A1). Consequently a family of curves of q vs. t_w is obtained for flow with dissociation at a given Reynolds No. where only one curve is obtained for flow with no dissociation.

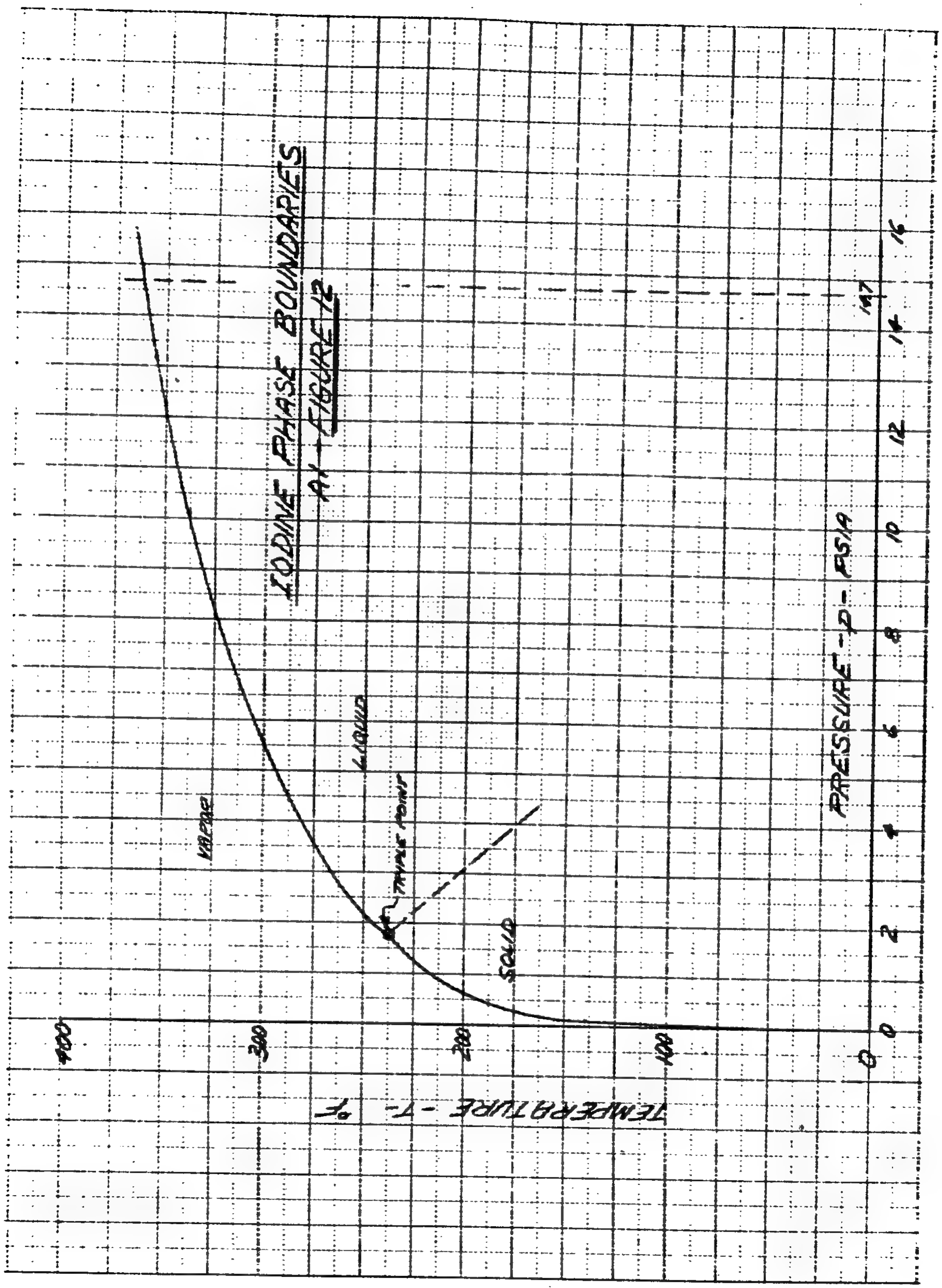
Figure 11-b is another way of showing the effect of dissociation on the heat transfer rate. The solid lines are for flow with no dissociation and the dashed lines show the effect of dissociation. For a given wall temperature the iodine temperature in the test section increases more at lower Reynolds numbers. Consequently dissociation will start at a higher pressure at lower Reynolds numbers.

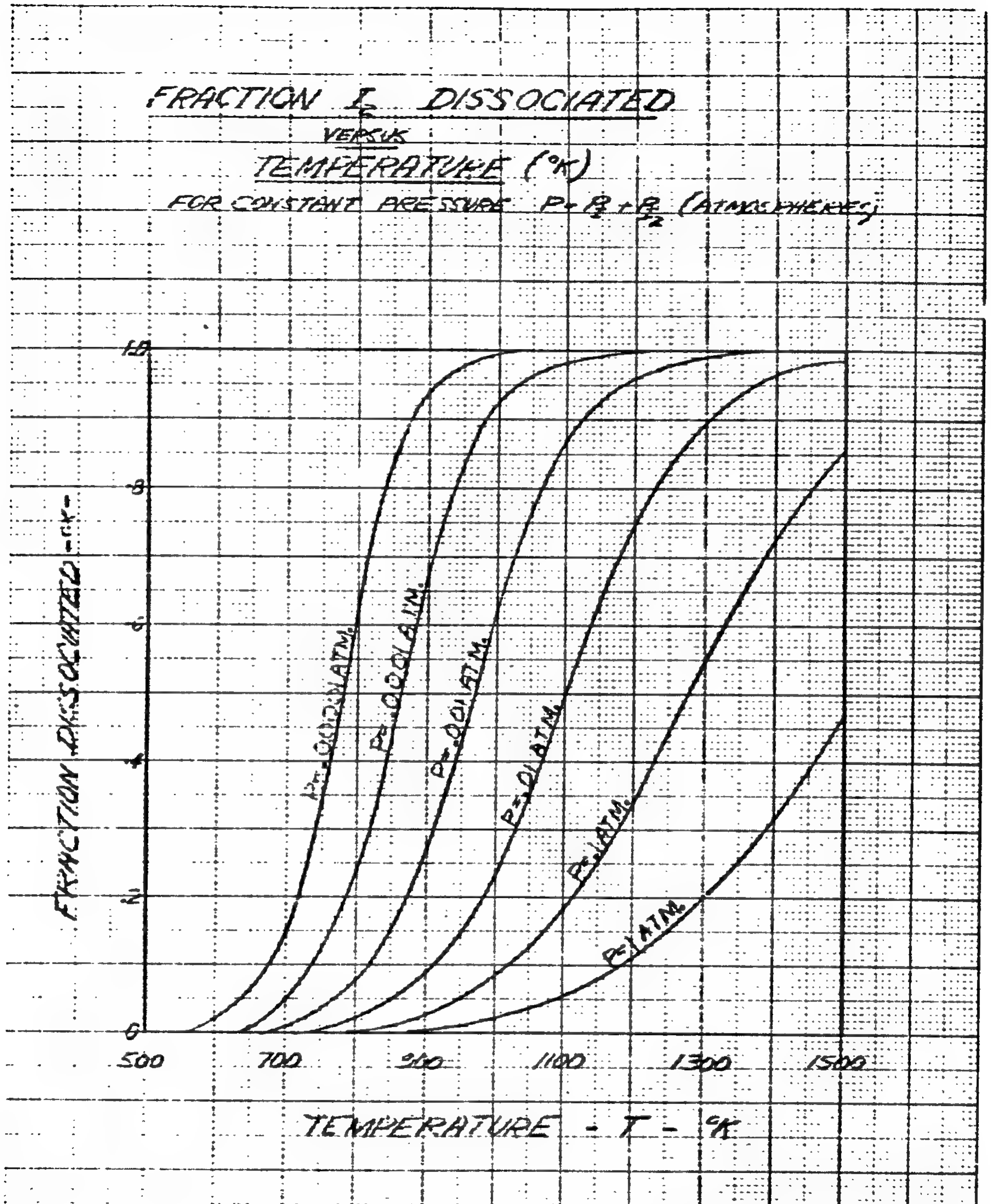
Figure 11-b is plotted for just one wall temperature. As the wall temperature is increased, the curves will be shifted upward and to the left.

The experimental heat transfer rates can be checked with the theoretical predictions based on laminar flow with variable properties. Heat transfer coefficients can then be obtained. If the experimental heat transfer results are in good agreement with the theoretical predictions, the experimental heat transfer coefficient will be the same as that calculated theoretically. The experimental heat transfer coefficient can also be determined from the data if some assumption is made about the temperature distribution in the test section. When dissociation occurs, the heat of dissociation affects the heat transfer rate and also any heat transfer coefficient that is calculated. Consequently, for dissociating flow the heat transfer coefficient is a function of this added variable and can be called an apparent heat transfer coefficient.

This suggested presentation of results is not necessarily complete. As experiments are made, more information will be obtained and a better understanding of the phenomena will be developed. A more complete method of presentation of results can then be worked out.

APPENDIX


IODINE PHASE BOUNDARIES
AT FIGURE 12
VAPOR
LIQUID
TRIPLE POINT
SOLID
PRESSURE - P - PSIA
0
2
4
6
8
10
12
14
14.7
16
TEMPERATURE - T - °F
0
100
200
300
400


FRACTION I₂ DISSOCIATED
VERSUS
TEMPERATURE (°K)
FOR CONSTANT PRESSURE P=P_I+P_I2 (ATMOSPHERES)
1.0
.8
.6
.4
.2
0
500
700
900
1100
1300
1500
FRACTION DISSOCIATED -α-
TEMPERATURE - T - °K
P=.00001ATM.
P=.0001ATM.
P=.001ATM.
P=.01ATM.
P=.1ATM.
P=1ATM.

A2- FIGURE 13

B1. CALCULATIONS FOR MODEL IN A FREE JET

The model considered is a flat plate one inch wide and three inches long in the flow direction. Table III (p. 15) shows the values obtained for radiation losses to a guard heater from one side of the flat plate (assuming a 5° temperature difference) and for convection to the iodine flow for various Reynolds Numbers.

For the q_c calculation, the equation used for determining the average h was taken from Eckert and Drake (3), p. 176.

$$\frac{\bar{h}x}{2k} = 0.332\ P_L^{1/3}\ Re_x^{1/2}$$

where properties are evaluated at $t = \dfrac{t_{wall} + t_{fluid}}{2}$

The model is assumed at 1500°F and the entering gas at 400°F. Then $q_c = \bar{h}A\,(T_{wall} - T_{fluid})$. The radiation heat transfer, assuming an emissivity of one, is given by $q_R = \sigma A(T_{wall}^4 - T^4_{guard\ heater})$.

B2. TEST SECTION HEAT TRANSFER

NOMENCLATURE:

Reference is made to the various components of the test section (see Figure 4, p. 19) which will be referred to as follows:

test tube - 3' long, 2" diameter tube whose wall temperature along entire length is to be kept at a constant temperature for a given test.

test data section - comprises the middle 12" of the test tube.

guard heater - 3' long, 5" diameter tube whose wall temperature along entire length is to be kept at the test tube temperature.

outer wall - the approximately 7" diameter tube outside the guard heater which will be kept at 400°F.

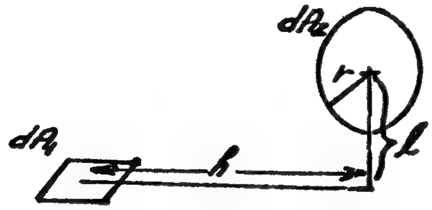
OBJECTIVE:

The purpose of these calculations will be: (a) to indicate that the heat transfer to the dissociating gas will be of sufficient magnitude in comparison with radiation and conduction losses from the test data section to allow meaningful measurements of the electrical input to the heaters; and (b) to determine the heater power requirements along the length of the test tube, guard heater, and outer wall.

RADIATION:

It is desired to find the heat loss from each one inch segment of the test tube out each end. The maximum test tube temperature of 1500°F will be used and it is

assumed the temperature radiated to is 400°F. The view vactor taken from p. 398, Eckert and Drake (3) is:



$$F_{1-2} = \frac{h}{2} \quad \frac{h^2+r^2+l^2}{(h^2+r^2+l)^2-4r^2} \quad -1$$

Taking a sample 1 inch long element of the test tube located between 12 and 13 inches from one end, the view factor becomes:

$$F_{12-13} = \frac{12.5}{2} \quad \frac{(12.5)^2+1^2+1^2}{(12.5^2+1^2+1^2)^2-4x1^2} \quad -1 \quad = 0.00056$$

and the heat loss out one end from this segment assuming a maximum emissivity of 1 is given by:

$$q_{12-13} = A_{12-13}\, F_{12-13}\, \sigma \,(T^4_{12-13} - T^4_s) = \pi\left(\frac{2}{12}\right)\left(\frac{1}{12}\right) \; x$$

$$.00056 \; x \; .171 \left[\left(\frac{1960}{100}\right)^4 - \left(\frac{860}{100}\right)^4\right]$$

$$q_{12-13} = .59 \; {}^{Btu}/Hr.$$

A plot of q in $^{Btu}/Hr.$ for each one inch segment along the tube length is shown in Figure 5 (page 22). From this it is estimated that the radiation loss out one end from the test data section at 1500°F is approximately 3 $^{Btu}/Hr.$

RADIAL CONDUCTION:

Insulation (Santocel) is to be placed between the test tube and the guard heater to cut down any radial conduction that would be caused by inability to keep guard

heater and test tube at exactly the same temperature. Assuming a 5°F temperature difference,

$$\text{q per foot of length} = \frac{k(2\pi L)\ \Delta T}{\ln r_2/r_1} = \frac{0.02(2\pi 1)5}{\ln 5/2} = 0.7\ \frac{\text{Btu}}{\text{hr.}}$$

For guard heater requirements, it must also be known how much heat is transferred between guard heater and outer wall.

$$\text{q per foot of length} = \frac{k(2\pi L)\ \Delta T}{\ln r_2/r_1} = \frac{0.02(2\pi 1)(1500-400)}{\ln 7/5}$$

$$= 410\ \frac{\text{Btu}}{\text{Hr.}}$$

<u>CONVECTION TO IODINE:</u>

Without considering the effect of dissociation, the magnitude of heat transfer to the iodine was determined as follows using the expression for laminar flow in a tube entrance region taken from Eckert and Drake (3), p. 198.

$$\overline{Nu_D} = 3.65 + \frac{0.0668(d/x)Re_D Pr}{1 + 0.04\ \left[(d/x)Re_D Pr\right]^{2/3}}$$

where: Nu and Pr are evaluated at $T = \dfrac{T_{wall} + T_{fluid}}{2}$,

and the Re is evaluated at T_{fluid} and is equal to

$4{,}140\rho V$ where ρ is in atmospheres and V in ft./sec. This results in the following $\bar{h}$ values for various Reynold's No's. with the wall at 1500°F and the entering iodine at 400°F.

Re	$\bar{h}$(1st foot)	$\bar{h}$(2 ft.)	$\bar{h}$(3 ft.)	$\bar{h}$(middle foot)	$\bar{h}$(end foot)
2,070	0.22	0.17	0.15	0.12	0.11
414	0.14	0.11	0.093	0.08	0.07
4	0.073	0.072	0.07	0.07	0.07

Assuming a constant temperature difference between the stream and the tube walls for the given values, q for the middle foot (the test data section) will range between 66 and 40 $^{Btu}/_{hr.}$ for Reynold's Numbers of 2,070 and 4 respectively.

To determine the maximum heater input necessary, the heat transfer to the gas at the Reynold's No. of 2,070 from each of the three one foot sections is determined using the $\bar{h}$ values from the above table and the formula $q = \bar{h}A\Delta T$. These q values are 127, 69, and 63 $^{Btu}/_{Hr.}$ respectively for wall at 1500°F and gas at 400°F. For heater input values, twice this magnitude will be allowed to make allowance for dissociation.

These values, as well as those of radiation and conduction loss, are shown as a function of test tube position in Figure 7 (page 27).

AXIAL CONDUCTION:

An extra amount of power will have to be supplied to the heaters at the two ends of the test tube to account for axial conduction. Using the maximum temperature difference between test tube temperature and wall temperature at the seal (1500 - 500°F), and using a $\frac{\Delta T}{\Delta X}$ based upon the

nozzle length,

$$q = kA\frac{\Delta T}{\Delta X} = k\pi D_{AVG}\, t_{AVG}\frac{\Delta T}{\Delta X} = 12\left(\pi\frac{4}{12}\right)\left(.\frac{2}{12}\right)\frac{1000}{.5}$$

$$q = 420\ ^{Btu}/Hr.$$

TOTAL MAXIMUM POWER TO TEST SECTION:

Excluding the small power needed for the heating tapes around the outer wall, the maximum requirements are as follows:

a) To test tube;

Radiation heat loss out 2 ends from test tube	$1100\frac{Btu}{hr.}$
Radial conduction	negligible
Convection to Iodine	$520\frac{Btu}{Hr.}$
Axial conduction at test tube ends	$840\frac{Btu}{Hr.}$

b) To guard heater;

Radial conduction to cooler outer wall	$820\frac{Btu}{Hr.}$
Total Maximum Power To Test Section =	$3280\frac{Btu}{Hr.}$
	≈ 1 kw

B3. SAMPLE CALCULATION FOR EFFECT OF IODINE DISSOCIATION ON HEAT TRANSFER

It is desired to determine the magnitude of heat transfer with I_2 dissociating to 2I in the laminar boundary layer to compare it to heat transfer with no dissociation. No references on internal flow with dissociation were known for calculation purposes so a reference on external flow was used for an order of magnitude calculation.

The equation

$$q/q' = 1 + \frac{Q\ Pr}{\bar{C}\ Sc\ Nm}\left(\frac{N_{i1}-N_{io}}{T1-T_o}\right)$$

by Altman and Wise (2) gives the ratio of heat transfer with chemical reaction to heat transfer with no chemical reaction. In this equation

q = heat transfer with no chemical reaction

q' = heat transfer with chemical reaction

Q = heat of reaction per mole of diffusing species

$Pr = \frac{C_p \mu}{k}$

$\bar{C} = \bar{M}\ \bar{C}_p$ where $\bar{C}_p$ is the average specific heat and $\bar{M}$ the average molecular weight

$Sc = \frac{\mu}{\rho D}$

O = diffusion coefficient

$( )_i$ = diffusing species

$( )_1$ = edge of laminar layer

$( )_o$ = property at wall

The diffusion coefficient for I_2 and I vapor could not be determined from present sources of iodine properties, therefore the ratio

Pr/Sc was assumed to be 1.

For T_o = 1000°K(1340°F) and Ti = 500°K(440°F) and an iodine pressure of 0.01 atmospheres the mole fraction of I_2 dissociated is 0.23 at the wall and 0 in the free stream. The other iodine properties calculated from values tabulated by Eastman (1) are:

$$\bar{C} = \bar{M}\,\bar{C}_p = 7.982 \frac{\text{cal}}{\text{gm mole°K}}$$

$$Q = 18260 \frac{\text{cal}}{\text{gm mole I}}$$

With the above properties the ratio

$\frac{q}{q'}$ = 10.15 showing that dissociation can increase the heat transfer appreciably.

B4. PRESSURE DROP CHARACTERISTICS

System pressure drop characteristics are calculated for the following components:

10 feet of 6 inch pipe

4-6 inch elbows

15 inches of 6 inch internally finned pipe, the equivalent diameter is D_{eq} = 1.91 inches (see Appendix B6.).

3 feet of 2 inch pipe

1-6 x 2 inch nozzle

1-2 x 6 inch diffuser

Calculations are based on average temperatures of 1000°F in the two inch pipe and 500°F in the six inch pipe and I_2 vapor only.

The head loss for the system in feet of iodine vapor is:

$$H_e' = \frac{V_6^2}{2g}\left[\left(f\frac{L}{D}\right)_6 + \left(f\frac{L}{D}\right)_{ells} + \left(f\frac{L}{D}\right)_{eq}\right] + \frac{V_2^2}{2g} \times$$

$$\left[\left(f\frac{L}{D}\right)_2 + c_n + c_D\right]$$

where

$\left(\frac{L}{D}\right)_{ells}$ = an equivalent length of straight pipe to compensate for elbow losses

$\left(\frac{L}{D}\right)_{eq}$ = an equivalent L/D based on Deq = 1.91 inches

c_n and c_D = loss coefficients for the nozzle and diffuser respectively

For comparison with fan characteristics it is helpful to change the head loss to inches of water based on standard air density. The conversion is

$$H_e = H_e' \frac{12\rho std}{\rho H_2O}$$

The flow is laminar everywhere, therefore

$$f = \frac{64}{Re}$$

Using this expression for f, the continuity equation, the definition of Reynolds number, and the perfect gas law for iodine vapor, the expression for head loss can be rearranged to give:

$$H_e = \frac{Re_2}{p^2} \frac{384\rho std}{\rho H_2O} \left\{\frac{\mu_2 RT_2}{D_2}\right\}^2 \left\{\frac{T_6{}^2\mu_6 D_2{}^3}{T_2{}^2\mu_2 D_6{}^3} \left[\left(\frac{L}{D}\right)_6 + \left(\frac{L}{D}\right)_{ells} + \frac{D_6}{Deq}\left(\frac{L}{D}\right)_{eq}\right] + \left[\left(\frac{L}{D}\right)_2 + \frac{Re_2}{64}(c_n + c_D)\right]\right\}$$

The values used in this equation are

$\rho std = 0.075\ ^{lb}/ft^3$

$\rho H_2O = 62.4\ ^{lb}/ft^3$

$\mu_2 = 2.46 \times 10^{-5}\ ^{lb}/sec\ ft$

$\mu_6 = 1.67 \times 10^{-5}\ ^{lb}/sec\ ft$

$\left(\frac{L}{D}\right)_{ells} = 4(12) = 48$

$c_n = 0.04$

$c_D = 0.58$

The $(\frac{L}{D})_{ells}$, c_n, and c_D were obtained from reference (4) and the iodine properties from reference (1).

Using these values the head loss is

$$H_e = 5.36 \times 10^{-11} \frac{Re_2}{p^2} \left[1950 + Re_2\right]$$

where H_e is in inches of water and P is the iodine pressure in atmospheres.

The volumetric flow rate is

$$Q = V_2 \frac{\pi D_2{}^2}{4}$$

or after rearranging

$$Q = 8.09 \times 10^{-4} \frac{Re_2}{p}$$ where Q is in cubic feet per minute and p is iodine pressure in atmospheres.

The pressure drop characteristics for the system were calculated from these equations for Reynolds numbers in the laminar range and pressures between 1 and 0.001 atmospheres. The results are plotted in Figure 8 (page 34).

The fan characteristics were obtained from Bulletin 770, Propellair Division, Robbins and Myers, Inc., Springfield, Ohio.

B5. FLEXIBLE COUPLING

The need for a flexible coupling is shown by a calculation for the difference in thermal expansion of the test section (316 stainless steel at 1500°F) and an equal length of 6 inch pipe (low carbon steel at 400°F) on the opposite side of the loop.

The change in length is:

$$\Delta L = L_o \alpha (T - T_o)$$

For the test section

L_o = 36 inches

$\alpha = 8.9 \times 10^{-6} \frac{in}{in°F}$ for 316 stainless steel

$T-T_o = (1500-80) = 1420°F$

Then

$\Delta L = 0.455$ inches

For 36 inches of 6 inch low carbon steel pipe

$\alpha = 6.6 \times 10^{-6} \frac{in}{in°F}$

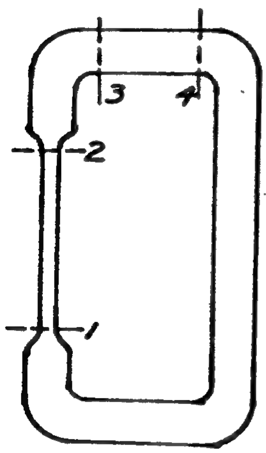
$T-T_o = 400-80 = 320°F$

$\Delta L = 0.076$ inches

The difference between the expansion of the two sides is then 0.379 inches.

B6. COOLING SECTION

For steady flow the amount of heat that must be removed from the iodine vapor after it leaves the test section is equal to the amount of heat transferred to the iodine in the three foot test section.



The amount of heat transferred to the iodine in the test section is

$$q = \bar{h}A\ \Delta T_{LM}$$

where $A = \pi DL$

and $\Delta T_{LM} = \dfrac{(T_w - T_2) - (T_w - T_1)}{\ln \dfrac{T_w - T_2}{T_w - T_1}}$

This is equal to the heat absorbed by the fluid which is

$$q = w\ c_p (T_2 - T_1)$$

Using these equations and the expressions for Reynolds number, Prandtl number, and Nusselt number, the following two equations can be derived for constant gas properties.

$$T_2 = T_w - (T_w - T_1)e^{-\frac{4Nu^{L}/D}{RePr}} \qquad \text{(A)}$$

$$q = \frac{\pi D}{4} RePr\ k(T_2 - T_1) \qquad \text{(B)}$$

All calculations in this section are made for I_2 gas assuming no dissociation. Average property values are taken for I_2 gas corresponding to a temperature of approximately 600°F. The assumed values which are used are

$$k = 0.0025 \frac{\text{Btu}}{\text{hr ft°F}}$$

$$Pr = 0.950$$

The dimensions of the test section are

$L = 36$ inches

$D = 2$ inches

The mean Nusselt number for laminar gas flow in a tube is a function of Re, Pr, and $\frac{L}{D}$. The mean Nusselt numbers for these calculations are taken from a plot of $\overline{Nu}$ versus $\frac{Re\,Pr}{L/D}$ for tube flow by Kays and London (5).

For the following assumed conditions

$T_w = 1500°F$

$T_1 = 450°F$

$Re = 200$

calculations yield

$\frac{Re\,Pr}{L/D} = 10.55$

$\overline{Nu} = 4.1$ (assuming parabolic velocity distribution for low Re in test section)

$T_2 = 1278°F$

$q = 51.5 \ ^{Btu}/Hr.$

For the same T_w and T_1 and $Re = 2000$ similar calculations yield

$Nu = 10$ (assuming Langhaar velocity profile because the flow won't be fully developed for Re=2000)

$T_2 = 782°F$

$q = 206 \ ^{Btu}/Hr.$

The most heating occurs at high Reynolds numbers for given inlet and wall temperatures, consequently more cooling

must be obtained for these conditions. For a test section Reynolds of 2000 the Reynolds number in the six inch pipe is approximately 666 as $Re \propto \frac{1}{D}$ for constant flow rate and constant viscosity. The length of six inch pipe at 400°F required to cool the iodine vapor from 782°F to 450°F when the test section Reynolds number is 2000 is calculated as follows:

$$q = h\pi DL \; \Delta T_{LM}$$

or after rearranging

$$L = \frac{q}{\pi \overline{Nu} \; k \; \Delta T_{LM}}$$

Numerical calculations yield

$$\overline{Nu} = 4.6$$

$$L = 35 \text{ feet}$$

This length of six inch pipe is not available in the apparatus, therefore some special cooling section is necessary. Even if the walls were cooled to 250°F, the temperature high enough to prevent iodine solidification at any pressure less than 0.1 atmospheres, the length of pipe required for cooling is 18.9 feet. Even this length of pipe is more than that available in the apparatus (approximately 15 feet).

To provide more heat transfer surface with a minimum pressure drop longitudinal fins will be welded in the 15" long horizontal piece of six inch pipe. Eighteen fins, nine 1.5 inches long and nine 0.75 inches long, can be welded inside a piece of 6 inch pipe. If welding construction were possible, additional fins could be added since the fin

effectiveness is shown to be nearly one.

The cooling that can be obtained with the above mentioned cooling section (see Figure 10, page 47) is calculated as follows: (I) The cooling before the finned sections is calculated to obtain T_3 and the q between 2 and 3; (II) The cooling in the finned section is calculated using an equivalent diameter and equivalent Reynolds number to obtain T_4 and q between 3 and 4; (III)The length of six inch pipes required to do the rest of the cooling is calculated.

For a test section Reynolds number of 2000 the cooling that can be obtained between 2 and 3 with a wall temperature of 400°F is

$$q = 12.4 \frac{\text{Btu}}{\text{Hr.}} \qquad \text{and}$$

$$T_3 = 762°F$$

For the finned section the equivalent diameter is defined as

$$D_{eq} = \frac{4 \times \text{cross sectional area}}{\text{wetted perimeter}}$$

For nine fins 1.5 inches long and 9 fins 0.75 inches long

$D_{eq} = 1.91$ inches

$$Re_{eq} = \frac{\rho V D_{eq}}{\mu} = 212$$

$$\overline{Nu} = 5$$

$$\bar{h} = \frac{Nu\ k}{D_{eq}} = 0.0728 \frac{\text{Btu}}{\text{hr ft}^2 °F}$$

The fin effectiveness is defined as

$$\eta = \frac{\tanh ml}{ml} \qquad \text{where} \qquad m = \sqrt{\frac{2h}{k\delta}}$$

and l = fin length

δ = fin thickness

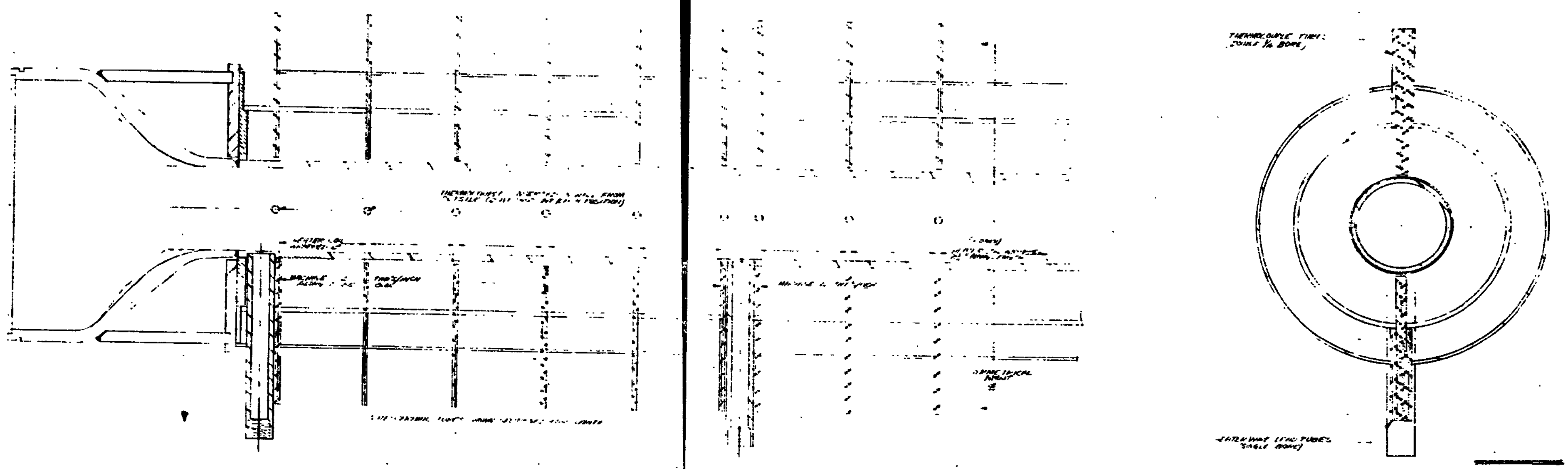
k = fin conductivity

h = heat transfer coefficient

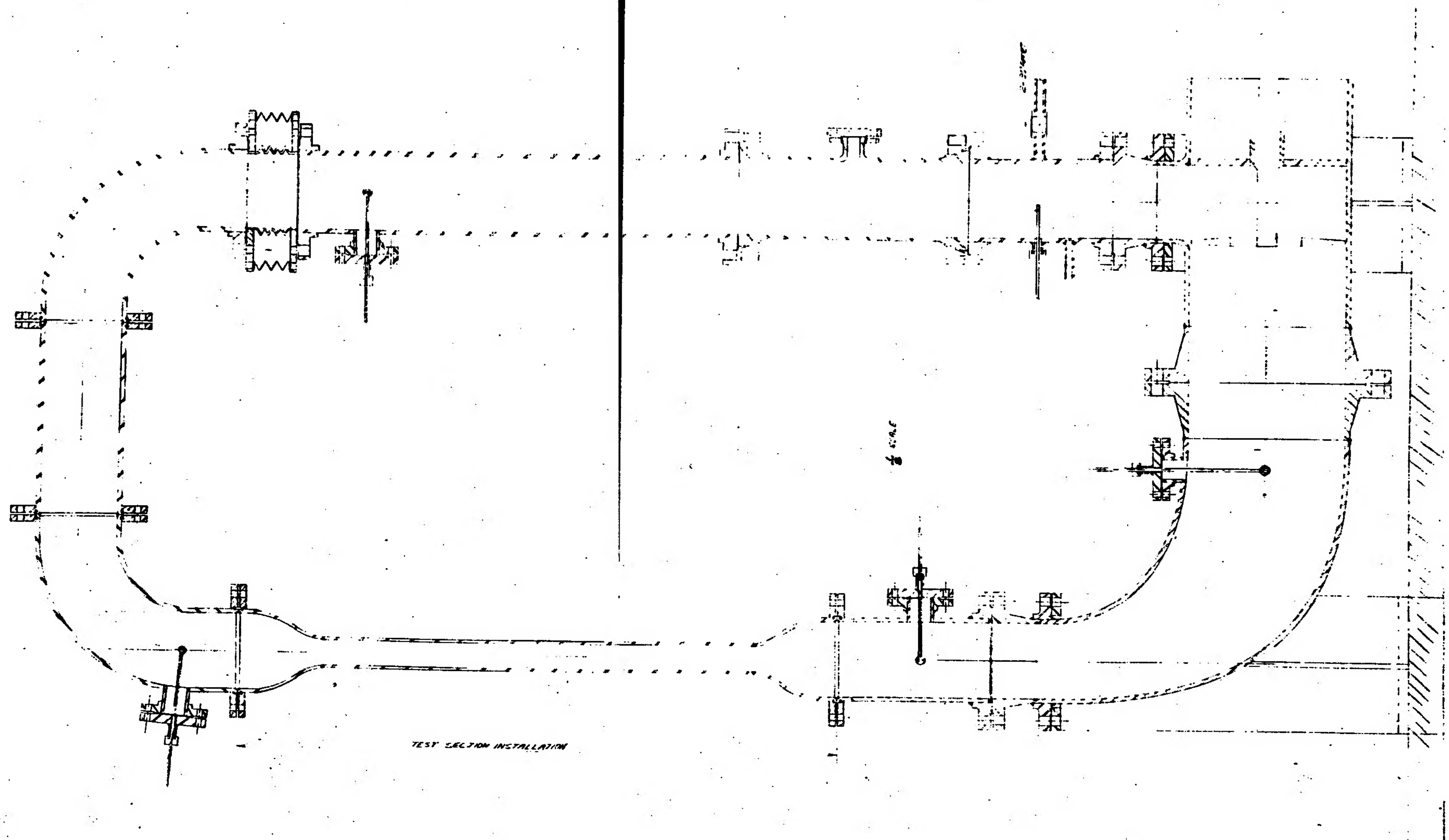
For a steel fin with l = 1.5 inches, δ = 0.125 inches, k = 25 $^{Btu}/hr\ ft°F$, and a heat transfer coefficient $\bar{h}$ = 0.0728 $^{Btu}/hr\ ft^2°F$ the fin effectiveness is 0.96. It shall be assumed equal to 1 for all calculations.

The cooling between 3 and 4 is calculated using equations (A) and (B). For a wall temperature of 400°F sufficient cooling cannot be obtained in the finned section. If the wall temperature in the finned section is reduced to 250°F the cooling that can be obtained is 150$\frac{Btu}{Hr.}$ for Re_{eq} = 212 and T_3 = 762°F. The amount of cooling that must be obtained after the finned section is then only 43.6 $^{Btu}/Hr.$ The length of six inch pipe at 250°F required to do this last amount of cooling is only 3.2 feet, an amount which is available in the apparatus.

C1 - Test Section Assembly

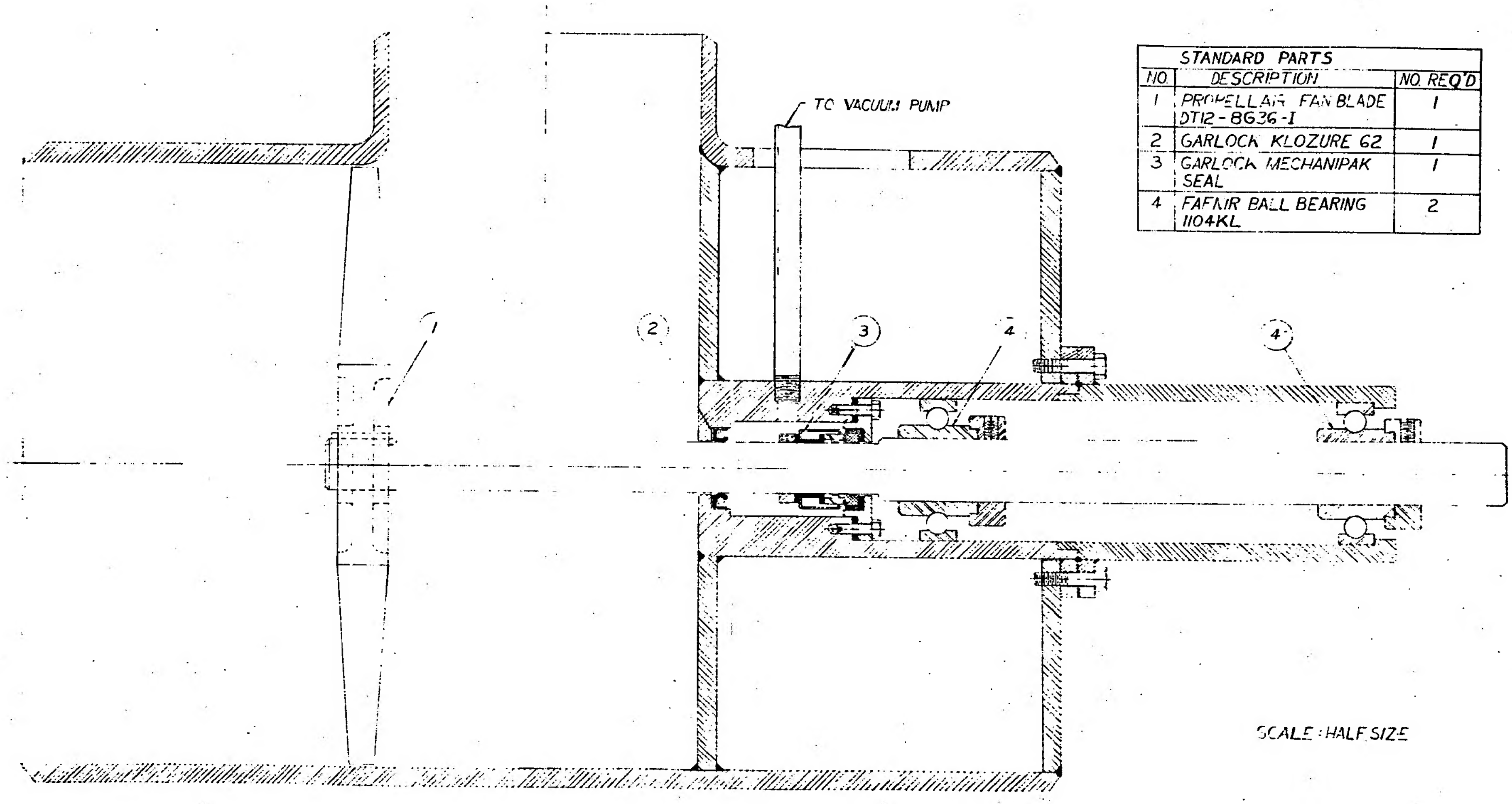


C2 - Tunnel Assembly



C3 - Fan Assembly

STANDARD PARTS		
NO.	DESCRIPTION	NO. REQ'D
1	PROPELLAIR FAN BLADE DT12-8G36-I	1
2	GARLOCK KLOZURE 62	1
3	GARLOCK MECHANIPAK SEAL	1
4	FAFNIR BALL BEARING 1104KL	2



NOMENCLATURE

A	area
c_p	specific heat
D	diameter
f	friction factor
F	radiation view factor
$\bar{h}$	average heat transfer coefficient
H_e	head loss
k	thermal conductivity
L	length
p	pressure
q	heat transfer rate
Q	volumetric flow rate
R	gas constant
T	temperature
ΔT_{LM}	log mean temperature difference
V	velocity
w	mass flow rate
Re	Reynolds number ($\frac{\rho VD}{\mu}$)
Pr	Prandtl number ($\frac{c_p \mu}{k}$)
$\overline{Nu}$	average Nusselt number $\frac{\bar{h}D}{k}$
α	coefficient of thermal expansion
ρ	mass density
σ	Boltzmann constant
μ	viscosity

<u>Subscripts</u>

$(\ )_2$	refers to two inch diameter
$(\ )_6$	refers to six inch diameter

BIBLIOGRAPHY

(1) Eastman, R. H., "An Experimental Apparatus for Heat Transfer Studies in a Chemically Reacting Boundary Layer", S.M.Thesis, M. I. T., 1959.

(2) Altman, D. and Wise, H., "Effect of Chemical Reactions in the Boundary Layer on Convective Heat Transfer", Jet Propulsion, Vol.26, p.256, 1956.

(3) Eckert, E. R. G. and Drake, R. M. Jr., <u>Heat and Mass Transfer</u>, McGraw-Hill Book Company, 1959.

(4) <u>Heating, Ventilating and Air Conditioning Guide</u>, Vol. 36, American Society of Heating and Ventilating Engineers, Inc., New York, 1958.

(5) Kays, W. M. and London, A. L., <u>Compact Heat Exchangers</u>, National Press, Palo Alto, 1955.

(6) Hunsaker, J. C. and Rightmire, B. G., <u>Engineering Applications of Fluid Mechanics</u>, McGraw-Hill Book Company, 1947.